

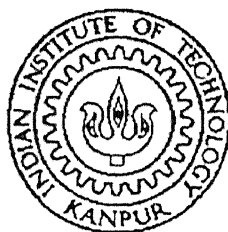
DESIGN OF INCINERATORS FOR HAZARDOUS WASTES DISPOSAL

A thesis submitted
in partial fulfillment of the requirements
for the degree of

MASTER OF TECHNOLOGY

by

B. SURESH BABU



to the

DEPARTMENT OF CHEMICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

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SYNOPSIS

In the initial stages of evolution of mankind, the waste disposal did not pose significant problems because the population was very less and the land available for disposal was large. Due to the high rate of growth of chemical process industries, thermal power plants, steel, leather and food processing industries, etc., large amounts of hazardous wastes are produced nowadays. These hazardous wastes pose significant problems like unhygienic conditions, land pollution, water pollution, air pollution, malodourous gaseous emissions, etc., leading to the epidemic and endemic diseases which are a major threat to the inhabitants of the earth. Hence, hazardous waste management should get utmost importance. The very first step in hazardous waste management is waste characterization. Present hazardous waste characterization mechanism, developed by CPCB, is a commendable work. Some of its minor flaws we hope would be rectified in the next revision. Some simple modifications are suggested to improve the present classification system. Hazardous waste classification guidelines are also developed and presented. A new hazardous waste indexing mechanism is proposed. This mechanism would be helpful in understanding the properties of wastes and also in the design of any disposal system. Various waste treatment and pretreatment methods are critically reviewed. Of the various treatment methods available, incineration is fast becoming an alternative final disposal method for the hazardous wastes. Different types of grates, hearths and feeding mechanisms used in typical incinerators are given. Various types of incinerators available, their suitability for different types of wastes, their advantages and disadvantages, etc., are critically reviewed.

Some important incinerator design concepts are developed and presented. Since the waste characteristics change continuously, the evaluation of operating parameters of an incinerator is very important. Two types of incinerators for two different types of wastes, (1) grate furnace for toxic organics (CPCB Waste Category 12) and (2) multiple hearth

furnace for pesticide industry waste (CPCB Waste Category 15), have been designed and detailed mass and energy balances are also presented. Possibilities of heat recovery for grate furnace design have been explored. Air pollution control measures to be taken are presented. A cyclone separator, a gas scrubber and a stack have been designed. Generation of poly chlorinated biphenyls (PCBs) and their control, need for continuous emission monitoring equipment, etc., are given. Ash and sludge management factors, safety precautions to be considered in an incinerator plant during startup, shutdown, operation, cleaning and transportation of hazardous waste are developed and presented. Capital and operating cost items have also been mentioned. Some of the promising areas for future work are also given.

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(B.Suresh Babu)

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Chapter 1

INTRODUCTION

And I say life indeed is darkness save when there is urge;
And all urge is blind save when there is knowledge;
And all knowledge is vain save when there is work;
And all work is empty save when there is love;
And when you work with love, you bind yourself to yourself, to one another
and to god.

Khalil Gibran.

Human and animal activities generate huge quantities of wastes which get accumulated day by day. Mushrooming of industries, fallacies, reluctance and perceptions of industrialists, leave alone natural calamities, add fuel to the fire. In earlier days the disposal did not pose significant problems, because the population was very less and the land available for disposal was large. These waste create lot of problems like unhygienic conditions, air pollution, malodorous gaseous emissions leading to epidemic and endemic diseases.

The assessment of health risks posed to humans by anthropogenic activities is an incredibly complex undertaking since there are lot of substances whose toxic potentials are yet to be established. This does depend on individual susceptibility too!

The practice of throwing wastes onto the unpaved streets, roadways and vacant land,

which is still being practiced in India and most of the developing and underdeveloped countries, lead to the breeding of rats with their attendant flea carrying germs of diseases and outbreak of *plague* and other. Diffusion of malodourous, toxic and poisonous gases into the atmospheric air, seepage of water through the waste either because of rain or streams, leaching from landfilled waste into groundwater, etc., pose a major threat to humans, animals and the vegetation.

Due to high rate of growth of chemical process industries (CPIs), thermal power plants, steel and leather processing industries, etc., huge amount of hazardous wastes are produced. Apart from these wastes, nuclear plants produce radioactive wastes. These radioactive and medicinal wastes also are very difficult to dispose off.

These wastes contain lot of carcinogens, pathogens, biologically active materials, radioactive materials, etc., which are a major threat to inhabitants of earth and to the earth too! Hence hazardous waste management should get utmost importance to save our planet from man-made calamities. Finding proper disposal methods, implementing them successfully and operating the plants honestly, are the need of the hour, not only to meet the stringent Pollution Control Board regulations but also for the reasons cited above.

There are a variety of disposal techniques available. Amongst them some are enlisted here. They are composting, landfilling, incineration, biochemical treatment methods, etc. A very brief description of the above mentioned methods are given in the second chapter. A comparison of these systems is also presented there.

The very first step in the design of any disposal system is to know the type of waste to be disposed off. A major problem with this is that we can not precisely predict the characteristics of the waste, since it keeps changing from time to time. So, it becomes impossible to design systems for one type of waste and operate for the other. It is wiser to design systems which can handle groups of wastes of varying characteristics. So waste characterization should be done in all cases and the third chapter is completely devoted

for the same.

The next step after characterization is pretreatment. All the wastes may not be suitable for treatment and disposal. They may be too watery or lot of metals and mud may present in it. These pitfalls can be overcome by properly pretreating the waste and making them suitable for further treatment. Various waste pretreatment methods and their applicability and suitability are discussed briefly in the fourth chapter.

In the design of incinerators, after the characterization and pretreatment are done, the next thing is waste feeding mechanism design. These waste feeding mechanisms depend on the characteristics of waste, type of incinerator selected, quantity of the waste and the capacity of the incinerator. Various feeding mechanisms and their suitability to particular system, etc., are critically analysed and summarised in the fifth chapter.

Incineration is a process by which waste is destructed thermally by combusting it. Various controversies related with it are enlisted in the sixth chapter. A comparison of incineration with other treatment methods is also presented. After incineration in the chamber, the effluent from the system and their subsequent disposal methods pose difficult problems. Various types of incinerators, their advantages and disadvantages are also discussed there.

The first and foremost thing in the incineration process is that the waste should be incinerable. After incinerable waste's characterization and pretreatment are done, suitable type of incinerator should be designed. Since waste composition changes from time to time, it is unwise to design on the basis of particular waste. After classifying the waste into various types, also in each type the characteristics keep varying. The best thing that could be done in these circumstances is to design an incinerator for a particular type and/or group of types for a fixed maximum quantity. Then various operating parameters like airflow, temperature, pressure, auxiliary fuel flow rate, excess air to be used, residence time of the gases, after combustion treatment plant's operating parameters, etc., can be

adjusted. This could be done by doing energy and material balances for each and every type of waste to be incinerated. It is very tedious and time consuming. Software could be of great help in this regard.

In the present design problem two types of incinerators of two tons per hour capacity each, for two types of hazardous wastes, are designed. Two types of incinerators, one grate furnace and the other multiple hearth furnace, have been designed. Complete material and energy balances, flue gas analysis of the both incinerator systems have been done for both types. Secondary combustion chambers have also been designed in order to enhance and ensure complete combustion. All these aspects including detailed design analysis are presented in the seventh chapter. Combustion takes place only in these two chambers. Ash produced in the system is collected and its disposal methods are also discussed. All wastes are not self combustible and heat content may not be sufficient to maintain combustion. To circumvent this problem, auxiliary fuel is added. Excess oxygen is used for complete combustion.

Incineration produces toxic, poisonous and/or malodourous gases. Some amount of particulate matter also come along with the stream. The effluent gas from secondary chamber contains large amount of heat in it. To recover waste heat the stream is passed through a heat recovery system. A brief discussion of waste heat recovery is given in the eighth chapter.

After the heat recovery system, the effluent pass through gas treatment section. It passes through a single or a series of cyclone separators and subsequently to an absorption tower for SO_2 removal. Finally the gases are sent to the stack. Apart from these, the ninth chapter also contains various aspects of air pollution, monitoring and control.

Ash from the primary and secondary chambers are mixed and sent to safe landfilling. Disposal of sludge generated in the absorption system is also discussed in the tenth chapter.

Incinerator plant startup, shut down, operation and safety guidelines are given in the

eleventh chapter. Some of the promising areas for future work have been enumerated in the twelfth chapter.

In the initial stages of evolution of engineering, the role of engineers is described and defined as converting low value materials into high value products. But the scenario has changed completely in course of time. Now our role includes not only the above but also to convert zero or no value hazardous waste materials into useful and/or harmless end products and subsequently to dispose them off safely, to save humans, animals and of course our planet!

Chapter 2

WASTE TREATMENT PROCESSES

If you care enough for the living
make a little space
make it better place
for you for me and the entire human race

Michael Jackson.

2.1 PHYSICAL PROCESSES

Physical processes can be defined as the processes in which the waste is separated into various fractions either by phase transfer or by some other methods, especially in the absence of chemical and biochemical reactions.

Physical processes do not destruct anything but separate out the waste into various fractions. Some or all fractions have to be treated further. Hence in general, the physical processes at the most achieve volume reduction of the hazardous wastes [1].

Physical treatment processes can be classified into the following groups.

1. Separation by differential action of a force.
2. Separation by differential passage through fixed media.
3. Separation by differential phase partitioning.

2.1 SEPARATION BY DIFFERENTIAL FORCE

Larger and smaller particles of differing densities or of same density, can be separated by the application of differential forces. Gravitational, centrifugal, magnetic, electrostatic forces can be used. In case of fluids, the differential application of a force upon the particle relative to the fluid, imparts a relative velocity between bulk fluid and the particle. This can be used for the separation. Various physical treatment processes with some examples are given in Table 2.1 [2].

Method of operation	Typical processes
Gravitational	Sedimentation
Centrifugal	Centrifugation
Magnetic	Magnetic filtration
Electric	Electrostatic precipitation, electro phoresis
<u>Separation by differential passage through fixed media</u>	
Granular	Granular, vacuum filtration, filter press, etc
Macromolecular	Ultrafiltration
Molecular	Reverse osmosis, dialysis, electro dialysis, etc
<u>Separation by differential phase partitioning</u>	
Liquid-liquid	Solvent extraction
Vapour-liquid	Distillation, absorption, air stripping, etc
Solid-liquid/solid-vapor	Adsorption

Table 2.1: Various physical treatment processes [2].

2.1.2 SEPARATION BY DIFFERENTIAL PASSAGE THROUGH A FLUID MEDIA

The basic principle involved in this process is to pass a stream through a medium of granular material, or a fabric and thus remove the suspended matter. These processes can be classified by the characteristic size of the particle, which are separated and hydraulic resistance. Some of the examples of these processes include vacuum filtration, pressure filtration, centrifugation, etc.

2.1.3 SEPARATION BY DIFFERENTIAL PHASE PARTITIONING

The waste to be treated is made to contact with another phase and certain contaminants of the waste get accumulated in the second phase. This is the basic principle of the separation by the differential phase partitioning. A novel example for this is physical decantation. Liquid-liquid separation, vapour-liquid separation, solid-liquid separation, solid-vapour separation, etc., can be effectively done by this process [1, 2].

2.2 CHEMICAL TREATMENT PROCESSES

Hazardous wastes can be chemically treated to nullify their toxicity and/or poisonous effects, by oxidizing or reducing them in a suitable atmosphere. Most of the chemicals involve multiphase reactions. Chemical waste treatment processes can be broadly classified into the following.

1. Neutralization.
2. Precipitation.
3. Oxidation/Reduction.
4. Ion Exchange.

5. Stabilization.

2.2.1 NEUTRALIZATION

Neutralization is a chemical treatment process by which the acidic or basic wastes are treated to lessen their acidity or basicity. Corrosive wastes can also be neutralized. Neutralization strongly depends on the pH of the solution.

- Acidic Waste Neutralization.

Methods of acidic waste neutralization include: (1) adding required amount of strong or weak base(s), (2) passing acidic waste through limestone beds, (3) mixing acidic wastes with lime or dolomite lime slurries, (4) mixing the acidic waste with a compatible alkaline, etc.

- Alkaline Waste Neutralization.

The most common method of neutralizing alkaline is by the addition of mineral acids. The following are the various methods of alkaline waste neutralization: (1) adding appropriate amount of strong or weak acid(s), (2) passing compressed gas to waste, (3) blowing flue gas through the waste, (4) mixing alkaline waste with a compatible acidic waste, etc.

2.2.2 PRECIPITATION

If a liquid waste contains a toxic constituent which is soluble in it, it may be possible to precipitate it out. The process by which a soluble constituent of a waste can be converted into an insoluble one and thus can be removed is known as precipitation.

Applications of precipitation generally focus on the removal of dissolved inorganic ions. Some of the typical examples, where precipitation is used in hazardous waste management include: (1) hydroxide or sulfide precipitation of heavy metals in solutions, (2) precipitation of barium or barium sulfate, (3) precipitation of silver and silver chloride, etc. The

formation of settling of inorganic precipitate is commonly termed as flocculation and sedimentation. These can effectively entrap both dissolved and colloidal organic contaminants via both physical and chemical mechanisms.

Co-precipitation involves the simultaneous precipitation of the contaminant of interest with other dissolved constituents through the addition of coagulants such as iron compounds or alums, sometimes together with lime to the waste.

2.2.3 CHEMICAL OXIDATION AND REDUCTION

There are a variety of oxidation and reduction methods available for the treatment of hazardous waste. They include thermal oxidation (incineration), catalytic oxidation, biological oxidation and reduction, chemical oxidation and reduction. These reactions are affected by kinetics of the reactions, pH, temperature of destruction, excess air used, residence time, turbulence, etc.

Incineration is more elaborately discussed in the sixth chapter. Various factors to be considered in the redox reactions in hazardous waste management are as follows:

1. Reaction driving force.
2. Stoichiometry.
3. How the process is done (batch wise, continuous, or semicontinuous).
4. Kinetic considerations.
5. System control and monitoring.
6. Safety considerations.

2.2.4 ION EXCHANGE

Ion exchange is a chemical treatment process used to remove dissolved ionic substances from contaminated aqueous streams. Anions and cations can be effectively removed by

these processes. It finds its extensive use in the softening of hard water, waste water treatment, etc.

2.2.5 STABILIZATION

The process by which liquid and semisolid wastes are converted into chemically stable solids, is known as stabilization. After the solidification process, the waste can be safely disposed off [2].

2.3 BIOLOGICAL TREATMENT PROCESSES

Organic materials can be destroyed, transferred and/or completely converted into inorganic by-products by the use of micro organisms. The survival of these micro organisms depend on the conditions of the atmosphere in which the waste is destructed. The kinetics of growth is a function of microbial population. If the concentration of the micro organisms keep decreasing, it should be increased by adding micro organisms continuously or intermittently.

Biological treatment processes can be broadly classified into the following two groups.

- Anaerobic processes.
- Aerobic processes.

2.3.1 ANAEROBIC PROCESSES

These are the processes, which are carried out in the absence of oxygen. Recent processes such as UASB (Upward Flow Anaerobic Sludge Blanket), etc., are widely used for the waste treatment and utilization of the treated waste. There is a plant in Jajmau, Kanpur.

In simple anaerobic digestion processes, waste is fed into a closed tank and digested one is withdrawn from the same on a continuous basis. This process has been widely used

for the treatment of municipal wastewater sludges. The process kinetics strongly depend on the following:

- Hydraulic residence time
- Volumetric loading
- Biomass concentration
- Solids residence time

2.3.2 AEROBIC PROCESSES

These processes are carried out in the presence of oxygen. In aerobic systems it is necessary to supply sufficient oxygen to the system to satisfy the requirements of micro organisms and to maintain a concentration of oxygen in the system such that dissolved oxygen is not the rate limiting. Appropriate amount of oxygen has to be supplied.

Aerobic processes tend to produce more sludge than anaerobic processes but the operation of anaerobic process is somewhat difficult [1, 3].

Any individual and/or combination of various methods described in this chapter can be utilized for treatment, pretreatment of wastes. Selection of a particular process and their suitability to the waste disposal are very important.

Chapter 3

WASTE CHARACTERIZATION

If one could predict the characteristics of the waste,
it would no longer be waste but utility.

One should know the characteristics of the waste before assessing the suitability of various treatment and disposal techniques. For the design of any treatment and disposal systems, waste characterization is the basis. The composition of the waste, characteristics, i.e. physical, chemical properties, etc., keep changing from time to time, location to location. So it becomes very difficult to design a system based on a particular type of waste. If the composition changes, all the design parameters change. The way to circumvent this problem is to have a standard design, and depending on the characteristics of the waste operating parameters should be adjusted. For example, by increasing or decreasing residence time, temperature of destruction, post treatment of effluents, etc. Only with the complete knowledge of the waste, the equipment needed and regulatory concerns to be followed, etc., could be determined.

The complexity of most organic chemical wastes reduce the ability to deal with their combustion on a purely theoretical basis [2, 4].

3.1 CHARACTERIZATION

In this chapter, general characterization waste is presented. Hazardous wastes can be classified into the following types.

1. Solid wastes
2. Liquid wastes
3. Gaseous wastes
4. Sludge wastes
5. Hospital wastes

Radioactive wastes does not come under the hazardous waste category.

After classifying the waste into the above classes, they can be further classified based on their physical, chemical and general characteristics, etc.

3.1.1 PHYSICAL CHARACTERISTICS

The following factors should be considered in the physical characterization.

For solids:

(1) Size distribution, (2) shape, (3) melting point, (4) bulk density, (5) ash content, (6) solubility, (7) volatility, (8) toxicity, (9) combustibility and (10) explosivity.

For liquids:

(1) Density, (2) viscosity, (3) vapour pressure, (4) flash and fire points, (5) percentage of solid contents, etc.

For gases:

(1) Composition of the gases, (2) temperature and pressure, (3) suspended liquid droplets and solid particles, etc.

3.1.2 CHEMICAL CHARACTERISTICS

General chemical characteristics:

(1) Flammability, (2) explosivity, (3) reactivity, (4) corrosive nature, (5) toxic effects on human, etc.

Thermochemical characteristics:

(1) Enthalpy, (2) stoichiometric air requirements for combustion, (3) heating value, (4) adiabatic flame temperature, etc.

Elemental composition:

(1) Carbon, (2) hydrogen, (3) sulfur, (4) phosphorous, (5) nitrogen, (6) oxygen, (7) heavy metals, (8) toxic materials, (9) alkali metals, etc.

Organics:

(1) Volatiles, (2) fixed carbon, etc.

3.1.3 GENERAL CHARACTERISTICS

In the general characteristics, (1) composition, (2) weight fractions of various materials, (3) weight fractions of combustible, non combustibles and recoverable materials are considered. Composition of waste by percentage solid, liquid and gaseous contents are also grouped with general characteristics.

Apart from the above classifications, the following list contains criteria used for matching different wastes to the various incineration facilities.

Physical form:

(1) Gas, (2) liquid, (3) slurry, (4) sludge, (5) solid contents.

Temperature range required for destruction:

(1) Greater than $1,100^{\circ}\text{C}$, (2) $760 - 1,100^{\circ}\text{C}$, (3) $370 - 760^{\circ}\text{C}$ and (4) less than 370°C .

For example, PCBs and dioxin wastes require greater than $1,100^{\circ}\text{C}$, toxic chemical wastes require 700 to $1,000^{\circ}\text{C}$ and non-hazardous municipal solid wastes require about 500°C for

their complete destruction.

Off gas generated:

Oxides of carbon, nitrogen and sulfur, halogenated products, phosphorous, volatile metals, etc.

Ash generated:

Non fusible, fusible or metallic particles.

Heating value:

Greater than 23 MJ/kg; 12 to 23 MJ/kg; less than 12 MJ/kg.

Figure 3.1 summarises various aspects of waste characterization.

The above classification is very general in nature. The Code of Federal Regulations (CFR, USA), has classified hazardous wastes as follows [1, 5].

- Ignitable waste: this waste will have at least one of the following properties.
 1. A liquid waste having flash point less than 60°C .
 2. A substance, other than a liquid which can cause fire, through friction or through absorption of moisture or by spontaneous chemical change under standard temperature and pressure.
 3. An ignitable gas.
- Corrosive waste: this waste will have either or both of the following properties.
 1. An aqueous waste with a $\text{pH} \leq 2$ (acidic) or ≥ 12.5 (basic).
 2. A liquid that corrodes carbon steel (grade SAE 1030) at a rate greater than 250 mils/yr.

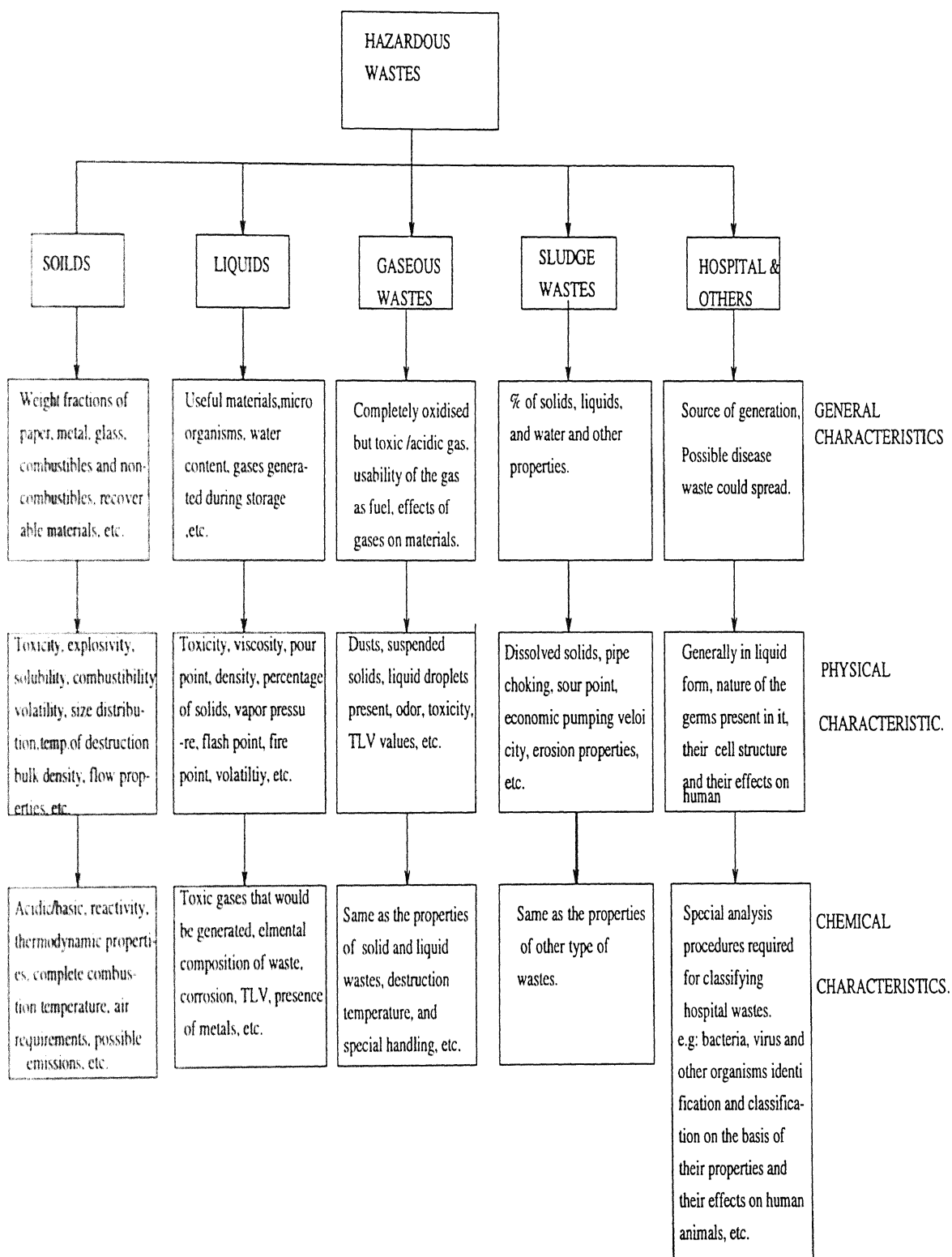


Figure 3.1: Waste characterization

- Reactive waste: this waste will have at least one of the following properties.
 1. A cyanide or sulfide bearing waste, which is itself harmful and may generate harmful gases, vapours or fumes when exposed to pH conditions between 2 and 12.5.
 2. A substance which is normally unstable and undergo violent physical or chemical changes without detonating, or which reacts violently with water.
 3. A substance that can generate harmful gases, vapours, fumes, when exposed to atmosphere or when mixed with water.
 4. EP toxic waste: in a sample of waste, if a particular constituent is greater than the allowable maximum concentration.
- Acute hazardous waste: a substance which is fatal to human beings in low doses, or in the absence of data on human toxicity, has been found to be fatal in corresponding concentrations in small animals.
- Toxic waste: wastes which have carcinogenic (tending to produce cancer), mutagenic (capable of inducing genetic mutations), or teratogenic (producing abnormal growth in fetuses).

Wastes can also be classified on the basis of their generation as follows:

- Wastes from non-specific sources.
- Waste from specific sources.

Wastes from non-specific sources are very difficult to characterize and handle. RCRA, USA (Resource Conservation and Recovery Act), has classified a lot of hazardous wastes. It has classified and grouped together more than 25 categories under non-specific wastes,

more than 100 under specific wastes, more than 100 under acute hazardous wastes and more than 250 under toxic wastes.

Central Pollution Control Board (CPCB), India has classified wastes into 18 categories [6] (please refer Appendix B). It is very difficult to classify the entire gamut of wastes into only 18 categories. While it is indeed a commendable work, there are certain drawbacks which we hope would be addressed during next revision by CPCB.

- Possibility exists of categorizing the wastes into more than one category. Some examples are given here.
 1. Cyanide wastes can be classified either as Category 1 due to the presence of cyanide or as Category 15 since pesticide industry waste has cyanide.
 2. Oily sludges can be classified either as Category 10 due to the presence of significant amount of oil or Category 16 due to the acidic nature.
 3. Tarry wastes under Category 11 during the manufacture of some of the bulk pesticides, tarry waste is generated from the recovery of solvent. But the existing classification system groups all pesticide industry waste under Category 15.
 4. Iron sludges containing phenols can be classified as Category 13 due to the presence of phenols or as Category 6, halogenated hydrocarbons including phenols.
- Existing classification does not give clear cut ideas about the waste. For example, acidic, basic and slurry wastes are all grouped under Category 16. However, it is very difficult by seeing the category number alone to predict whether it is acidic or basic.
- The existing classification system does not give information of waste toxicity, reactivity, corrosivity, flammability, explosivity, etc.

3.2 HAZARDOUS WASTE INDEX

Some suggestions are given to improve the existing hazardous waste classification system.

A new hazardous waste indexing mechanism and codes to identify different types of wastes to indicate all the potential hazards they possess are also proposed. Hazard index values for individual chemicals can be found in Ref [7].

Codes for different wastes:

Waste category	Code
Flammable wastes	F
Chronic toxic waste	T
Acute toxic wastes	A
Corrosive wastes	C
Reactive wastes	R
Explosive wastes	E

Table 3.1: A new coding system

Waste index representation: $[code(s)]_{index}pH$

3.2.1 FIRE AND REACTIVITY HAZARD INDICES

FIRE INDEX OF THE WASTE

A weighted average value for fire index is calculated as follows:

$$Fire\ index = \sum x_i N_{Fi} \quad (3.1)$$

where x_i is the mass fraction of waste constituent 'i', and

N_{Fi} is the fire index value of the component 'i'.

Waste fire index values will range from '0' to '4'.

ACTIVITY INDEX OF THE WASTE

above, a weighted average value for reactivity is also calculated.

$$\text{Reactivity index} = \sum x_i N_{Ri} \quad (3.2)$$

where N_{Ri} is the reactivity index value for component 'i'.

2.2 TOXICITY HAZARD INDEX

The above weighted average method is not applicable for toxicity hazard index calculations. For example, highly toxic materials whose presence even in traces (e.g.: less than one percent) is also unacceptable. But if we calculate the index assuming the following, lead to wrong conclusions. A sample analysis is shown in Table 3.1.

Constituents	% composition	Hazard index
Highly hazardous	1% (TLV \leq 0.1ppm)	4
Non-toxic	99%	0

Table 3.1: Toxicity hazard index calculation: incorrect method

The Index value is 0.04; this shows that the waste has very low hazard. But, in actual practice the waste is still unacceptable, and highly hazardous one.

As an alternative, the following procedure is proposed to calculate the hazard index.

$$\text{Toxicity index} = \sum \frac{x_i}{TLV_i} * 100 \quad (3.3)$$

where TLV_i is the threshold limit value of component 'i'.

Lower the TLV value, higher the hazards associated with. Hence, TLV comes in the denominator. TLV values have been chosen instead of other measures such as LD_{50} , LC_{50} , etc., since TLV gives the most safe values. If the calculated index is high, we can also think of reducing the value to an acceptable, or at least to a less hazardous value, thus minimizing the potential devastations involved therein.

Chemicals whose TLV value is less than 1 ppm (e.g.: cyanide, arsenic, PCB, etc.), should be categorised under highly hazardous group, if they are present in detectable levels.

The toxicity hazard index value for minimum TLV value of 1 ppm and detectable concentration of 0.001%, is 0.001 (assuming all other components are non-toxic); the index value would be 100, if all the waste is pure and whose TLV is 1 ppm. Some sample calculations are shown .

Case (1):

Waste characteristics:

Component	Percent composition	TLV	Hazard index
A	0.001	1	0.001
B (non-toxic)	99.999	-	-

Table 3.3: Toxicity hazard calculation: case (1).

Toxicity hazard index is 0.001.

Case (2):

Waste characteristics:

Component	Percent composition	TLV	Hazard index
A	100	1ppm	100

Table 3.4: Toxicity hazard index calculation: case (2).

Toxicity hazard index = 100.

Toxicity hazard index acceptable values can be fixed up by local regulatory bodies.

3.2.3 DETERMINATION OF WASTE INDICES

Here some examples to determine waste indices are given.

Case (1):

Waste characteristics:

Component	% Composition	N_F	N_R	TLV_i
A	40	3	3	10 ppm (<i>acute</i>)
B	20	2	1	25ppm (<i>chronic</i>)
C	15	0	4	200 ppm (<i>chronic</i>)
D	25	0	0	-
		$\sum x_i N_{F_i} = 1.6$	$\sum x_i N_{R_i} = 2.0$	$\sum \frac{x_i}{TLV_i} * 100 = 4.875$

Table 3.5: Waste index calculation: case (1)

Corrosion rate from past experience or some projected or expected value, if available can be included in the index. In this example, we have assumed corrosion rate to be over 1 mm/yr. Hence corrosion factor is 0.5 [8].

Inference from case(1) index:

$$\text{Hazardous waste index} = A_{4.875} C_{0.5} F_{2.0} R_{2.0} pH3$$

1. The waste has acute toxicity; index value is very high, hence, unacceptable.
2. Corrosion factor is very high (corrosion rate is greater than 1 mm/yr).
3. It is a flammable mixture at relatively high ambient temperatures (fire index value '2' represents materials that must be moderately heated, or exposed to relatively high ambient temperature before ignition can occur [9]).
4. Reactivity is also very high (reactivity index value '2' represents materials which are themselves unstable and readily undergo violent chemical reaction but do not detonate [9]).

5. Waste is acidic in nature and its pH value is '3'.

Case (2):

Waste characteristics:

Component	% Composition	N_F	N_R	TLV_i
A	10	2	0	2 ppm (acute)
B	20	4	1	25ppm (chronic)
C	70	-	-	-
		$\sum x_i N_{F_i} = 1.0$	$\sum x_i N_{R_i} = 0.2$	$\sum \frac{x_i}{TLV_i} * 100 = 5.8$

Table 3.6: Waste index calculations: case (2).

In this example, we have assumed that the waste could produce stress cracking and corrosion factor for this condition is 0.75 [8] and its pH value is 4.5.

Inference from case(2) index:

$$\text{Hazardous waste index} = A_{5.8} C_{0.75} F_{1.0} R_{1.0} pH_{4.5}$$

1. Corrosion rate is very high and utmost care should be taken.
2. Flammability is very less (fire index value '1' represents materials that must be prepared before ignition can occur [9]).
3. Reactivity is very less (reactivity index '1' represents materials which in themselves are normally stable but which can become unstable at elevated temperature and pressure [9]).
4. Waste is acidic in nature and its pH value is 4.5.

From the information above, some important safety precautions to be taken, material of construction to be used, and not used, etc., can be developed at the waste generation cite itself, which can be used all along till the waste could be safely disposed off.

3.2.4 USES OF WASTE INDEX

1. In transportation of hazardous waste.
2. To understand the nature of the waste for non-technical personnel, truck drivers, loading, unloading personnel, for regulators, district authorities, etc.
3. To develop handling procedures. (i.e., low index does not mean that we have to take less precautions, but to take more precautions when the index value(s) is (are) high, and also what all to do to bring the index down, etc.)
4. To decide what materials of construction to be used in incineration equipment, transportation vessels, storage vessels, tanks, etc.
5. In the design of any disposal system (e.g.: (1) incineration equipment design, safety precautions to be taken, extra features to be added to the existing system, etc., (2) in landfilling, layer thickness design, materials to be used, etc., (3) air/ash pollution control measures to be taken, etc.).

The very first step in hazardous waste management is waste characterization. Some of the flaws of existing CPCB classification system are enumerated. Some remedial measures have also been suggested. Once we know the characteristics of the waste, a suitable waste disposal method, waste pretreatment methods, air pollution, land pollution control measures to be considered, safety precautions to be taken, materials to be used etc., can be easily determined.

Chapter 4

WASTE PRETREATMENT

On the other hand
we can not ignore efficiency.

Jon Bentley.

Waste pretreatment techniques are used in waste management systems to improve the efficiency of operation, to recover usable materials and to recover products and energy. In this chapter some of the important pretreatment techniques are discussed. They are:

1. Mechanical volume reduction (e.g.: compaction).
2. Chemical volume reduction (e.g.: burning, precipitation, etc.).
3. Mechanical size reduction (e.g.: shredding, grinding, etc.).
4. Component separation (e.g.: manual and mechanical).
5. Drying and dewatering.

4.1 MECHANICAL VOLUME REDUCTION

In almost all the solid waste management systems, volume reduction is an important factor. Volume reduction has to be done in order to reduce the volume required for landfilling,

to reduce the transportation costs and to reduce open storage area required. Compaction equipment are most widely used for mechanical volume reduction.

4.1.1 COMPACTION EQUIPMENT

Compaction equipment used in volume reduction can be broadly classified into two groups: stationary and movable.

Stationary compactors may be described according to their application as (1) light duty, (2) commercial or light industrial, (3) heavy duty and (4) transfer station [4].

COMPACTION EQUIPMENT SELECTION

Important factors that must be considered in the selection of compaction are:

- Characteristics of the waste to be compacted including size, composition, moisture content and bulk density.
- Methods of transferring and feeding waste to compactor.
- Compactor design characteristics.
- Operational characteristics including energy requirements, simplicity of operation noise level, air pollution control requirements, etc.
- Site considerations including space, height, access, noise and related environmental limitations.

Reduction in volume is represented as follows.

$$\text{Percent volume reduction} = \frac{V_i - V_f}{V_i} * 100 \quad (4.1)$$

where V_i = initial volume of the waste,

V_f = final volume of the waste.

The ratio of initial to final volume is known as the *compaction ratio*.

Thus, the compaction ratio = V_i/V_f

The bulk density of waste, moisture content, etc., which vary with the characteristics of the wastes are the important factors which affect the design of the compactors.

4.2 CHEMICAL VOLUME REDUCTION

Various chemical processes are used to reduce the volume of the solid wastes. Burning the waste is a common practice at many disposal sites. Incineration is the most important method in the gamut of chemical volume reduction. This process is discussed in detail in the sixth chapter. Other chemical processes involved in volume reduction of wastes are *Pyrolysis*, *Hydrolysis*, *Chemical conversion*, etc [1, 4, 10]. These processes are generally used to recover usable materials.

4.3 MECHANICAL SIZE REDUCTION

The main objective of size reduction is to enhance the combustion efficiency by making the final product of a reasonable uniform and reduced size in comparison to its original. It is important to note that size reduction does not necessarily imply volume reduction. In some cases the total volume of the material may be greater than that of the original one. Here some of the principal types of the equipment, their suitability and their applicability are briefly discussed.

4.3.1 SIZE REDUCTION EQUIPMENT

Various types of equipment are used in homogenizing solid wastes. They include small grinders, chippers, large grinders, jaw crushers, shredders, hammer mills, hydro pulpers,

etc. Grinding, mashing, slicing breaking, shearing, tearing and cutting are some of the modes of actions involved in these equipment.

SELECTION OF SIZE REDUCTION EQUIPMENT

The following are some of the important factors that must be considered in the selection of equipment for size reduction.

1. Characteristics of wastes and the products that is desired.
2. Required size of the wastes material.
3. Type of operation (continuous or intermittent).
4. Operational characteristics including energy requirements, routine maintenance, etc.
5. Site consideration.
6. Methods of feeding.

Size reduction is very difficult in the case of highly sticky materials.

4.4 COMPONENT SEPARATION

Whenever energy and combustion products are to be recovered from wastes, component separation should be done. It can be classified into two types. They are manual component separation and mechanical component separation.

4.4.1 MANUAL COMPONENT SEPARATION

HAND SORTING

The manual separation of solid waste components can be accomplished at the source where solid wastes are generated, at a transfer station, at a centralised processing station, or at the disposal site. Typically hand sorted components include newspaper, aluminum,

glass, cardboard, plastic wraps, metals, wood from commercial and industrial sources; and metals, wood and bulky items of value from transfer stations and disposal sites.

4.4.2 MECHANICAL COMPONENT SEPARATION

Various techniques and equipment involved in the mechanical separation are discussed in this section.

AIR SEPARATION

Air separation is mainly used to separate out the lighter fraction from the waste. This technique is used to separate out paper products, plastic materials and other light organic materials from the waste stream [4].

Processed solid wastes are dropped into a vertical chute. Air is blown upward from the bottom. This transports the lighter materials to the top of the chute. Heavier products are collected from the bottom.

Characteristics of the material produced by shredding, material specifications for light fraction, column design characteristics including solids to air ratio (w/w), fluidizing velocities, operational characteristics including energy requirements are amongst the most important factors that must be considered in the selection of air separation equipment. Figure 4.1 shows an air separation arrangement [4].

MAGNETIC SEPARATION

Magnetic separation systems can effectively be employed to recover ferrous scrap from shredded wastes. This can be done either before air classification or after air classification. Magnetic separation is also used to remove ferrous materials from incinerator ash/residue. Magnetic recovery systems have also been used at landfill disposal sites.

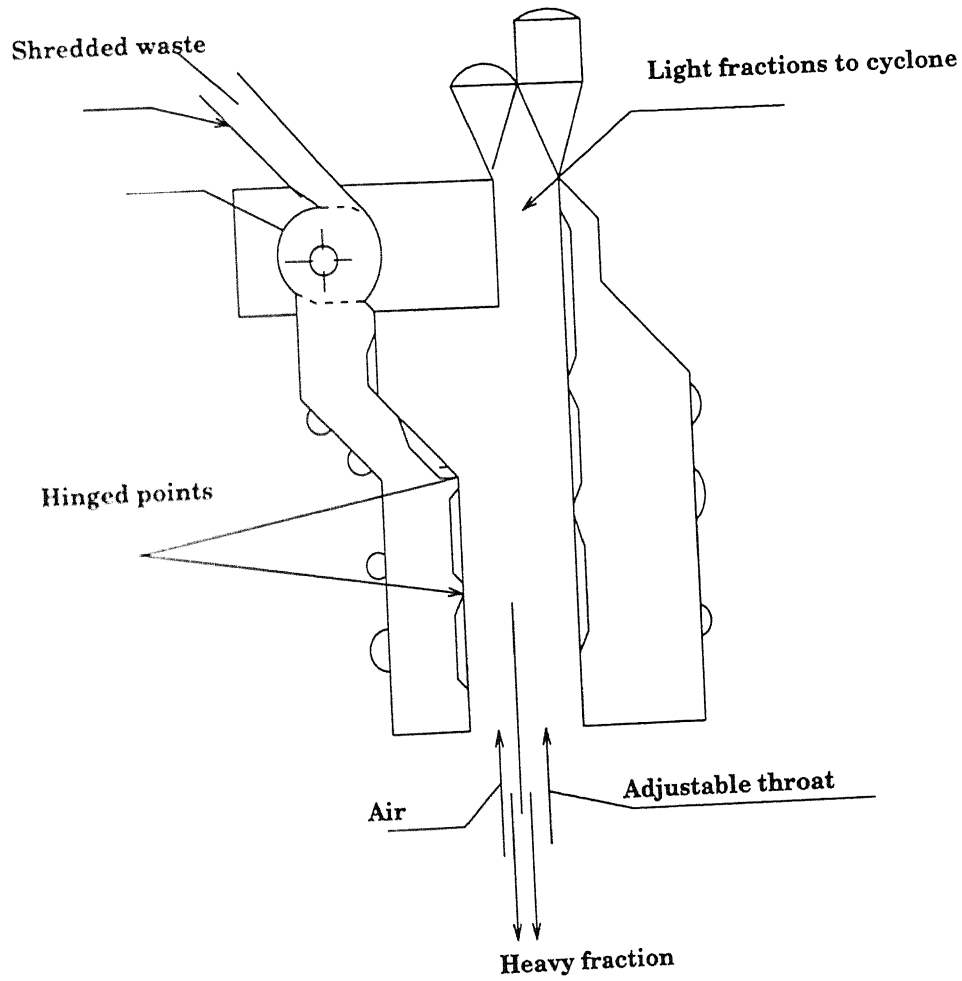


Figure 4.1: Air separation [4].

MAGNETIC SEPARATION EQUIPMENT

In a typical magnetic separation system, the waste material is carried by belt conveyors. Magnetic drums provided at the end, picks up the magnetic materials (ferrous materials, for example). Most of the non-magnetic materials (non-ferrous materials) fall to a take away conveyor located below the primary separator. Figure 4.2 shows a typical magnetic separator arrangement [4].

SCREENING

Screening is an important method involved in the separation of mixture of materials of different sizes into two or more portions by means of one or more screening surfaces. Screening may be accomplished either wet or dry, with the latter being most common in solid waste processing systems. Screening can be used before shredding and after shredding. Screening separates out the waste into various fractions only on the basis of size whereas air separation method separates only on the basis of density [4].

4.4.3 OTHER SEPARATION TECHNIQUES

Some of the other separation techniques used are enlisted here [11]. Inertial separation and electrostatic precipitation are discussed in the ninth chapter.

- Inertial separation.
- Flotation.
- Optical sorting.
- Electrostatic precipitation.
- Heavy media separation.

Inertial separation and electrostatic precipitation are discussed in ninth chapter.

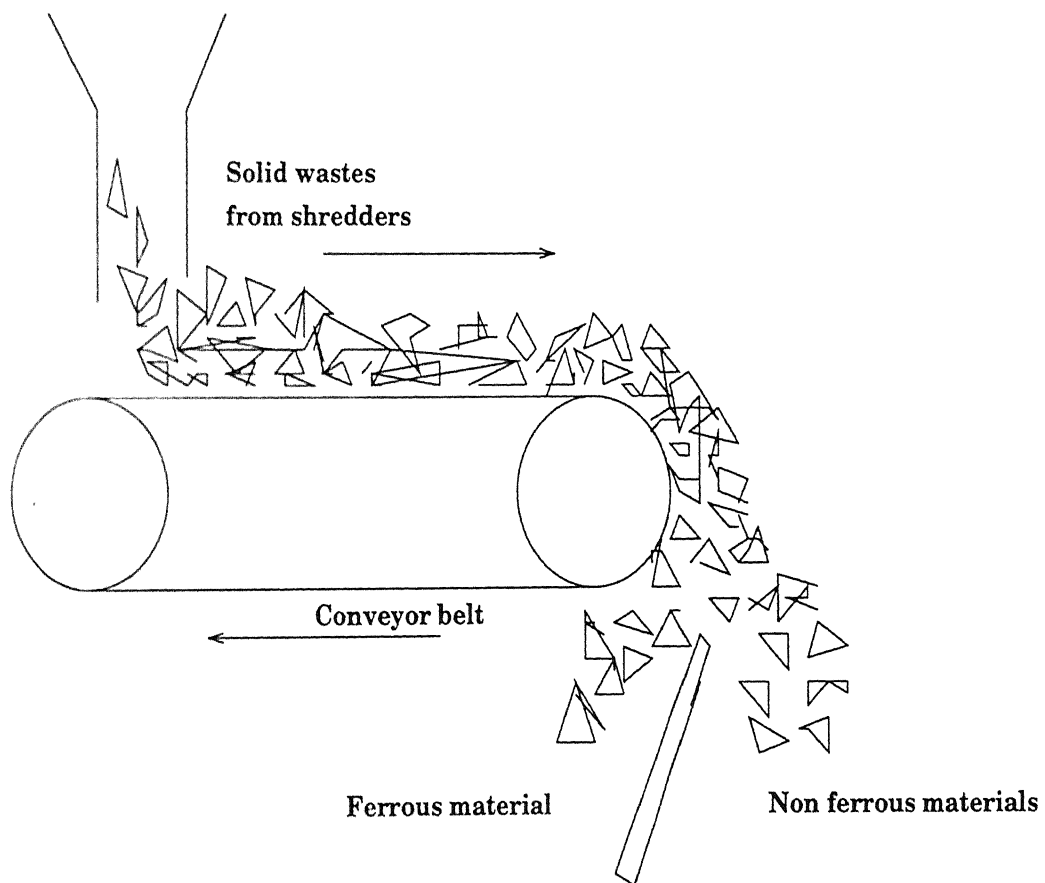


Figure 4.2: Magnetic separation [4].

4.5 DRYING AND DEWATERING

In solid waste energy recovery and sludge incinerations, it is very important to pre-dry the waste to decrease the weight by removing varying amounts of moisture, depending on the process requirements. In case of waste water sludge treatment (incineration) dewatering improves the efficiency of operation and reduces the operating costs.

4.5.1 DRYING

Drying the wastes can be accomplished either by conduction, convection, or radiation, or by their combination(s).

Operational characteristics of various dryers and their modes of operations can be found in the literature [4, 11].

Energy requirements are the major limiting factors in drying of wastes. Highly toxic materials have to be dried in a closed environment. This increases the operational difficulties.

4.5.2 DEWATERING

Dewatering should be done for the following reasons.

- To reduce the load to the incinerators.
- To reduce the volume required for landfilling.
- To reduce the amount of auxiliary fuel added to the waste for incineration, etc.

Centrifugation and filtration are two general methods now used most commonly to dewater water treatment plant sludge.

CENTRIFUGATION

It is possible to produce a reasonably thick sludge (10 to 15 percent water content) by means of centrifugation. Bowl, decanting, and horizontal centrifuges are used to dewater sludge. The most critical problems involved with these operations are, (1) operation and maintenance costs and (2) carryover of fines in the lighter medium [3, 11].

FILTRATION

Vacuum and pressure filtration can be used to dewater the sludge. If the toxic materials are soluble then, filtrate may contain some amount of toxic materials dissolved in it. Then some other methods should be employed [3].

The very first step in waste management is that the waste should be characterised (Chapter 3). Then suitable methods of disposing it should be thought of. Depending on the treatment methods selected, the waste should be pretreated. One or more of the waste pretreatment techniques discussed in this chapter can be employed to increase the efficiency of the treatment operation and of course, to reduce the operating costs.

Chapter 5

FEEDING MECHANISM, HEARTHS AND GRATES

I hear and I forget, I see and I remember,
I do and I understand.

Chinese Proverb.

5.1 FEEDING MECHANISM

Pretreated waste is fed to the incinerator either by batch or continuously and the recent trend has been toward the use of continuous feeding to improve process control. In most cases, batch feeding of the refuse into the furnace is done with a clamshell bucket. The rate of feed is controlled by the time cycle and the degree of bucket loading. In a few plants, a front-end loader operating on a paved floor charges the furnace [12].

5.1.1 RAM FEEDING

For controlled feeding, ram-type feeding device is used sometimes. With such a system, either a ram can clear the hopper at each stroke or an oversized hopper can be filled with refuse and the ram is used to sheer a horizontal section of refuse at selected intervals. The ram feeder provides an air seal at the feed to the furnace, an improvement over the bucket

or front-end loader systems of batch feeding, which usually let in undesirable quantities of cold air, as well as releasing occasional puffs of hot gases while the charging gate is open. If the cold air enters into the incinerator, it would be detrimental to the inside refractory walls of the furnace and can cause smoke evolution by cooling and quenching the burning process. In such cases, an air seal should be used. A two-gate airlock during batch feeding to keep the air out can be used but this increases the height of the incinerator feeding system, cost, and maintenance problems.

5.1.2 CONTINUOUS FEEDING

Continuous feeding mechanism can be accomplished by means of a hopper and gravity chute, a mechanical feeder such as a pusher, a ram, rotary feeder, or the like, which can be filled directly from a hopper supplied with refuse by a bucket and crane; a front-end loader from a feeding floor; a conveyor transporting the refuse from receiving area; an air injection system, etc. The most frequently used system is the hopper and gravity chute [4, 12].

A rectangular hopper receives the refuse delivered by the crane and bucket. The bottom of the hopper terminates in a rectangular section chute leading downward to the furnace grate or other feeder conveyor at the entrance of the furnace chamber itself.

If suspension burning is desired in the furnace the refuse should be prepared by suitable shredding or grinding, and the most desirable feeding method is air injection. Suspension burning is used successfully in waterwall boilers for generation of steam from waste products. With suspension burning, a burnout grate is provided at the bottom of the waterwall furnace to permit complete combustion of larger particles and/or slow burning materials.

5.1.3 LIQUID WASTE FEEDING

For rapid vaporization, the exposed liquid surface area for heat transfer must be increased. Most commonly the amount of surface exposed to heat is increased by finely atomizing the liquid to smaller droplets, usually to 40 μm size or smaller.

The degree of atomization achieved in any burner depends on the kinematic viscosity and on the amount of solid particles present. In some cases, the waste is pretreated to reduce kinematic viscosity (before atomization).

Solid impurities in the waste can interfere with the burner operation by plugging, erosion and ash buildup on the nozzle. Both the concentration and size of the solids, relative to the diameter of the nozzle, need to be considered. Filtration may be employed to remove solids from the waste prior to injection through the burner.

Liquid wastes are fed into the incinerators by anyone of the following means [1, 5].

1. Rotary cup atomizers.
2. Single-fluid-pressure air atomizers.
3. Two-fluid, low pressure air atomizers.
4. Two-fluid high pressure air or steam atomizers.

ROTARY CUP ATOMIZERS

The rotary cup consists of an open cup mounted on a hollow shaft. The cup is spun rapidly and liquid is admitted through the hollow shaft. A thin film of liquid to be atomized is centrifugally thrown from the lip of the cup and surface tension reforms it into droplets. Conical shaped flames are achieved by directing an annular high velocity jet of air axially around the cup [1].

SINGLE-FLUID-PRESSURE AIR ATOMIZERS

In single-fluid pressure atomizing nozzle burners, the liquid is given swirl as it passes through an orifice with an internal tangential guide slots. Disadvantages of this system are erosion of the burner orifice and the tendency to be plugged by solid or liquid pyrolysis products particularly in smaller sizes.

TWO-FLUID, LOW PRESSURE AIR ATOMIZERS

In typical low pressure atomizers air from blowers at pressures from 107 *kPa* to 140 *kPa* is used to aid atomization of the liquids. Less excess air is required as the atomizing pressure is increased. The flame is relatively short, because up to 40% of the stoichiometric air may be mixed with the liquid in atomization

TWO-FLUID, HIGH PRESSURE AIR OR STEAM ATOMIZERS

High pressure two-fluid burners require compressed air or steam at pressures from 310 *kPa* to 1,135 *kPa*. The major disadvantage of such burners is the ability to burn barely pumpable liquids without further viscosity reduction. Steam atomization also tends to reduce soot formation with waste that would normally burn with a smoky flame [2].

5.2 HEARTHS

Nearly all incineration furnaces employ either a refractory hearth to support the burning or a variety of grate types which stoke or mix the refuse during the combustion process in various ways depending upon the type of grate or stoker.

Hearths can broadly be classified into the following three major groups: (1) stationary hearths, (2) rotary hearths, and (3) rotary kilns.

5.2.1 STATIONARY HEARTHS

The stationary hearth is usually a refractory floor to the furnace, which may have openings for the admission of air under slight pressure below the burning material on the hearth. In some cases, air is admitted along the sides of the furnaces. Roof air nozzles inject air from the top of the furnace [13].

If furnace side nozzles and/or roof nozzles are used, combustion proceeds in the same manner as in a bonfire but with improved conditions due to the re-radiation of heat from the surrounding furnace walls and roof. It is necessary to provide manual stoking with slice bars to stir the mass of the refuse in order to achieve a reasonable degree of burnout.

Stationary hearth furnaces are used for most commercial and small industrial incinerators. They are also used for crematoria and for hospital wastes assisted with auxiliary gas or oil burners to maintain the furnace temperature above 650°C to 900°C . A refractory door permits the opposite side of the combustion chamber to be opened for access. A special extended bulldozer blade can be used to load the hearth with refuse from a paved platform outside the chamber and to drag out ash residue. Alternatively, it is possible to remove the ash residue by raking with a hoe or by pushing the residue beyond the hearth into a depressed area from which the ash can be removed (please refer section 6.2.2 for more details and figure).

5.2.2 ROTARY KILN

The rotary kiln type of hearths are used in the pyro-processing industries and in the high temperature combustion zones to mix the waste during combustion by rotating them. The steel cylindrical grate is lined with abrasion resistant refractory to prevent overheating of the metal, unless special provisions are made for air cooling or water cooling. The kiln is inclined toward the discharge end, and the movements of the solids being processed is controlled by the speed of rotation [5, 12].

5.3 GRATES

Mechanically operated grates can be classified into the following two groups: (1) mechanically operated grates for batch operations, and (2) mechanically operated grates for continuous operations.

5.3.1 MECHANICAL GRATES: BATCH OPERATIONS

Batch type grate furnaces employ either cylindrical furnace grates or rectangular furnace grates.

CYLINDRICAL FURNACE GRATES

In the cylindrical furnaces the grates form annuli inside the vertical cylindrical walls of the furnace. A dead plate covers the central area of the annulus. Mechanical stoking or mixing is provided by a hollow rotating hub with extended rabble arms, above the circular dead plates.

Wastes can be fed intermittently or batch wise through an opening in the top, at the centerline of the furnace. A charging door is used to close the opening between additions of refuse. It is necessary to poke and slice the ash residue using the access doors around the furnace and also to clean the furnace and to assist in the dumping of the ash residue.

RECTANGULAR BATCH FURNACE GRATES

Rectangular batch operated furnaces include reciprocating grates and rocking grates. These grates are installed in a slightly inclined position from the horizontal. At times it is necessary to manually stoke or slice the fire in order to spread the refuse over the grate or remove larger pieces of metals or clinkers that interfere with the desired flow of burning refuse across the grate.

5.3.2 MECHANICAL GRATES: CONTINUOUS OPERATION

In continuous burning incinerators the flow rate of the feed should be maintained constant throughout. This constant flow grate feeds the refuse continuously from the refuse feed chute to the incinerator furnace, provides movement of the refuse bed and ash residue toward the discharge end of the grate, and does some stoking and mixing of the burning materials on the grates. Grates for continuous operations can be classified into the following.

- Reciprocating grates
- Rocking grates
- Traveling grates
- Vibrating, oscillating and impact grates
- Drum grates

RECIPROCATING GRATES

Wastes are moved through furnace from the hopper while grate is actually stationary except for alternative reciprocating movement of component stoker bars. Action stoker bars turn wastes over and then tumbles them forward to the next successive stoker bars. Two or more grates are commonly included for a continuous flow incinerator [1, 2, 4]. A typical reciprocating grate is shown in Figure 5.1 [4].

ROCKING GRATES

Operation is similar to reciprocating grate but wastes are moved through the furnace by rocking actions. The rocking grate also slopes downward from the feed toward the discharge end, with two or more grate sections installed in series with little or no drop-off between

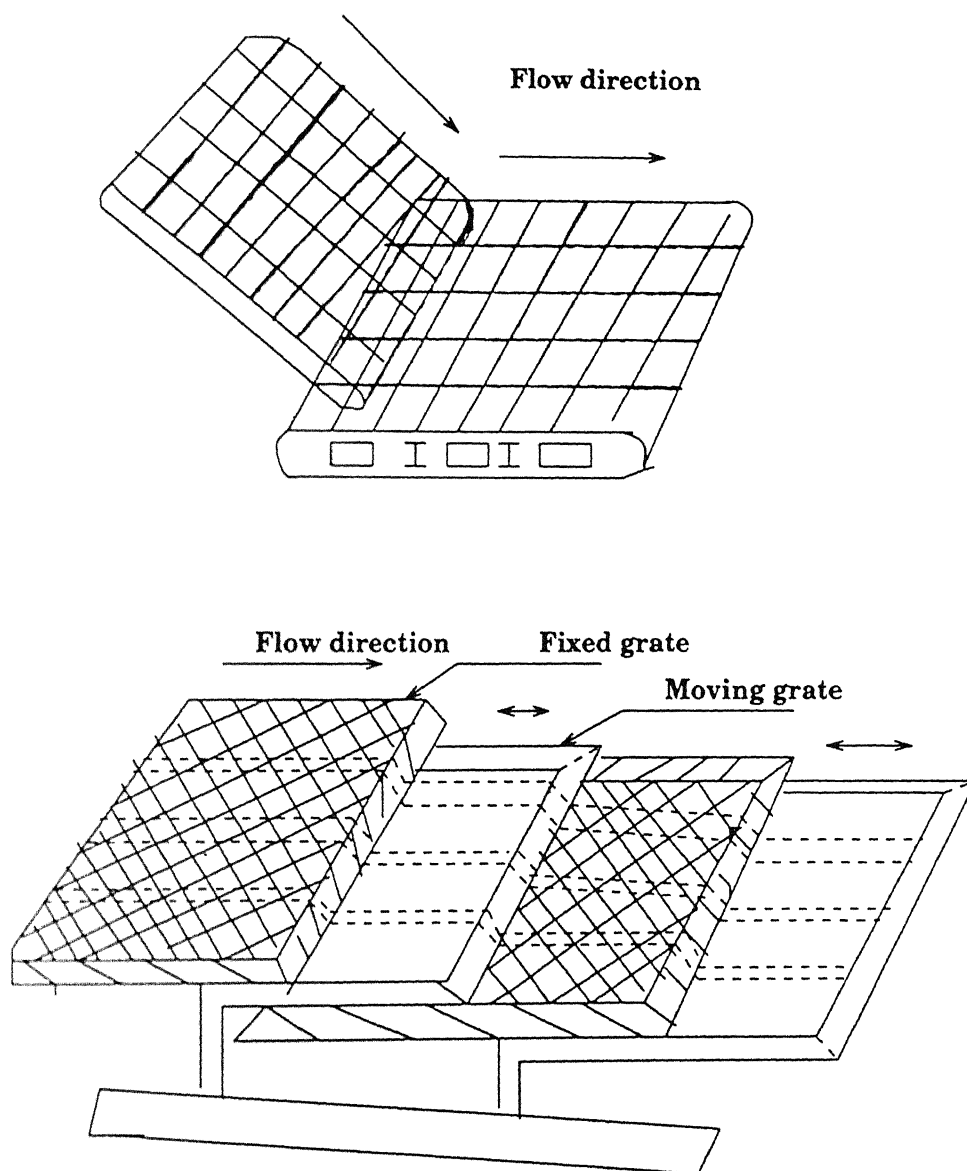


Figure 5.1: Traveling and reciprocating grates [4].

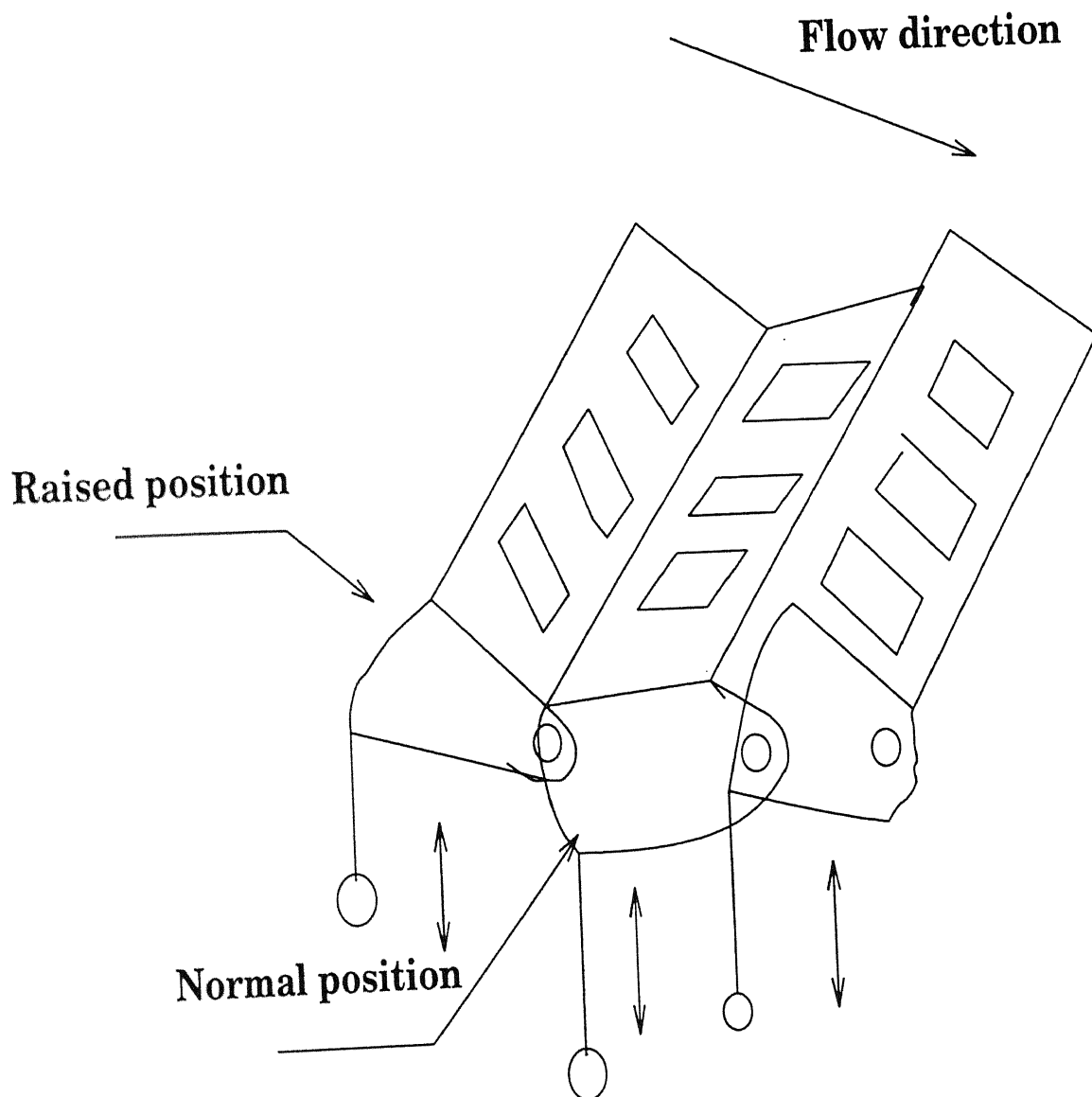


Figure 5.2: Rocking grate [4].

grate sections. Alternate rows of grate sections are rotated approximately 90° about the edge toward the discharge end of the grates, with grate face rising up into the burning mass and thus breaking it up and thrusting it forward toward the discharge end. These grate sections each rotate back to a rest position and alternate sections rotate as before, causing a similar stoking action and pushing of the refuse bed forward. A rocking grate arrangement is shown in Figure 5.1 [4].

TRAVELING GRATES

The traveling grate is widely used in continuous flow incinerator furnaces. It consists of a continuously moving feeder grate and one or more burner grates. Feeder grate is located directly under a charging door from which waste fall onto grates. Wastes are partially dried while on feeder grate. Figure 5.2 shows a typical traveling grate arrangement.

There are two types of traveling grates: the chain grate and the bar grate. Both convey the refuse from a gravity feed chute through the incinerator furnace to the residue discharge end, much as a conveyor belt. Incinerator traveling stokers are often cascaded in one or more units. The first portion under the feed chute and continuing through through the ignition zone, is often called as the feeding or drying stoker. The discharge from this first portion of the traveling grate spills and tumbles onto a second unit, thereby mixing, breaking and redistributing the bed on the second stage.

VIBRATING, OSCILLATING AND IMPACT GRATES

The vibrating or oscillating grate is mechanically powered by an eccentric weight vibration generator or an eccentric driven connecting rod. The oscillations convey the refuse through incinerator furnace from one grate section to the next, in the same manner as an oscillating or vibration conveyor. In the impact stoker or grate, the grate sections are moved either forward or in the reverse and then released for spring return against an impact [10, 12].

DRUM GRATE

Drum grate is sometimes called the barrel type grate. It is a relatively new design. Wastes are burned as they are moved by a series of rotating barrels. Each rotating drum or cylinder represents a minimum length of a traveling grate section, thereby providing a maximum number of tumbling zones in waste/refuse bed. The slow rotation of the drum create a strong mixing action in the refuse between successive drums. The rotating cylinders extend over the width of the furnace (width of the grate) and each cylinder is equipped with its own variable speed drive to control the movement of the burning refuse through the incinerator. Thus the rotating drum grate provides better control of refuse stoking and residence time during combustion than the the traveling grate, with consequent improvements in burnout [4, 12].

Depending upon the characteristics of the waste, type of the incinerator selected and quantity of waste to incinerated, suitable feeding mechanism should be selected.

Chapter 6

INCINERATION

Nothing would be done at all if man had waited till he could
do it so well that no one could find fault with it.

Cardinal Newman.

Incineration is a thermal treatment process by which the waste is burnt to ashes, in the presence of excess oxygen, to reduce the hazardous nature and/or toxicity of the wastes. Some reduction of the wastes are also achieved by incineration. Incineration can also be used as a controlled combustion process for reducing solids, liquids, sludges and gaseous combustible wastes primarily to carbon dioxide, other gases and relatively non combustible residue. In this chapter, comparison of incineration with other processes, various types of incinerators, their advantages and disadvantages are presented [14].

1 COMPARISON OF INCINERATION WITH OTHER TREATMENT PROCESSES

There are several types of processing techniques available that may yield a useful end product from the wastes. One of the techniques is composting.

3.1.1 COMPOSTING

Composting is a biochemical degradation of organic materials to a sanitary nuisance free material. Modern composting methods have been described as a rapid but partial decomposition of moist solid organic matter by the use of aerobic/anaerobic micro organisms under well controlled conditions.

Composting is compared with incineration and results of the analysis are given below.

1. All the wastes are not biodegradable/incinerable.
2. For a specific amount of waste, biodegradation process takes sufficiently long time when compared with the incineration processes.
3. Partial destruction of the wastes by biodegradation produces gases which may be toxic and/or nuisance to the residents nearby.
4. Leaching of the wastes by groundwater, rain water, etc., may lead to contaminated ground water and this pose a major threat to the humans, animals, who consume it.
5. Operating costs as well as fixed costs of incineration is higher than the biodegradation plants.
6. If the waste is combustible as well as biodegradable, reasonable amount of heat could be recovered by incinerating the waste, which may be used to generate steam and/or power.
7. Some important environmental concerns relate to the production of odors, the blowing of loose materials and the possibility of heavy metal toxicity to the land.
8. Land area requirements for composting plants are higher than the incineration plants [4].

3.1.2 LANDFILLING

The term landfilling means an operation in which the wastes to be disposed of are compacted and covered with a layer of soil/concrete at the end of each day's operation. When the disposal site has reached its ultimate capacity -that is, after all disposal operations have been completed - a final layer of 60 cm or more of cover material is applied. Advantages and disadvantages of landfilling are summarised here [15].

ADVANTAGES OF LANDFILLING

1. When land is available, a sanitary landfill is usually the most economical method of solid waste disposal.
2. The initial investment is low compared with other disposal methods.
3. A sanitary landfill is a complete or final disposal method as compared to incineration and composting which require additional; treatment or disposal operations for residue, gaseous effluents, etc.
4. A landfill can receive all types of solid wastes, eliminating the necessity of separate collection.
5. A sanitary landfill is flexible; increased quantities of solid wastes can be disposed of with little additional personnel and equipment.

DISADVANTAGES OF LANDFILLING

1. In highly populated areas suitable land may not be available.
2. Proper landfill standards must be adhered to.
3. Landfill located in public areas may provoke extreme public opposition.
4. A completed landfill will settle and require periodic maintenance.

5. Methane, an explosive gas and other gases produced from the decomposition of the wastes may become a hazard and nuisance and interfere with the use of the completed landfill [3, 16]. Contamination of groundwater by leaching, as discussed earlier, is also a major disadvantage of landfilling.

6.1.3 INCINERATION

Incineration is becoming more attractive as an alternative hazardous waste disposal method [1, 5, 12, 17, 18, 19].

ADVANTAGES OF INCINERATION

1. The destruction of the hazardous components is almost complete.
2. Volume and weight of the waste are reduced to a fraction of their original values [5].
The reduction is typically of the order of 80 to 90 percent [4].
3. Waste destruction is immediate; it does not require long-term residence time as in a biological treatment pond or as in other land disposal systems.
4. Wastes can be incinerated at site of their production [18].
5. Air discharges can be effectively controlled for minimal impact on the environment.
6. If the ash residue and sludge from the absorber(s) become non-hazardous, incineration becomes a final disposal method as well as a treatment method for hazardous waste.
7. Incineration requires a relatively small disposal area, not the many acres needed for lagoons and other land disposal methods.
8. Incineration is easily terminated. The cessation of incineration activity will remove any future liability for the operator.

9. Through heat recovery techniques, the cost of operation can be reduced or offset by the use or sale of energy.

DISADVANTAGES OF INCINERATION

1. Highly aqueous wastes and non-combustible solids are not incinerable.
2. Metal fumes emission from the incineration process may be difficult to control/eliminate for inorganic wastes with heavy metals content (e.g.: lead, cadmium, mercury, nickel, arsenic, etc.).
3. Incineration represents a high capital cost.
4. Auxiliary fuel is required to bring up an incinerator to operating temperature and, with some materials, to maintain the combustion temperature.
5. Air pollution, ash residue, sludge disposal, auxiliary fuel, etc., increase the operating costs of the incinerators [1, 5].

6.2 TYPES OF INCINERATORS

There are several types of hazardous waste incinerators. The prominent amongst them are:

- Rotary-kiln incinerators.
- Multiple hearth incinerators.
- Multiple chamber incinerators.
- Fluidized bed incinerators.
- Liquid injection incinerators.

- Infrared incinerators.
- Open-pit incinerators.

6.2.1 ROTARY-KILN INCINERATOR

The rotary-kiln incinerator is a cylindrical shell lined with fire bricks or other refractory and mounted at a slight incline. Rotating the shell mixes the waste with the combustion air. This rotation provides turbulence and agitation to maximize the burnout. Rotary-kiln can handle solid, liquid, sludge and gaseous wastes [5]. Rotary-kiln can handle solid with heating values from 550 to 8,250 $kcal/kg$. Typical throughput of solids ranges from 45 kg to 1.8 metric tons per hour. Kilns are usually co-fired with fuel or liquid wastes to sustain the combustion of solids with low heat content [1]. The kiln is maintained with a negative draft to assure that the leakage is into the system and that no hot dirty/toxic gases leak out of the kiln to the surrounding area [20]. Figure 6.1 shows a typical rotary-kiln incinerator [1].

ADVANTAGES

1. Can incinerate wide variety of liquid and solid wastes.
2. Availability of many types of feeding mechanisms.
3. No moving parts in the kiln.
4. Provides high turbulence and air exposure to solids.
5. Residence time of the waste can be controlled by adjusting the rotating speed of the kiln.
6. Minimal waste preprocessing required.
7. Can be operated at temperatures in excess of $1,400^{\circ}C$.

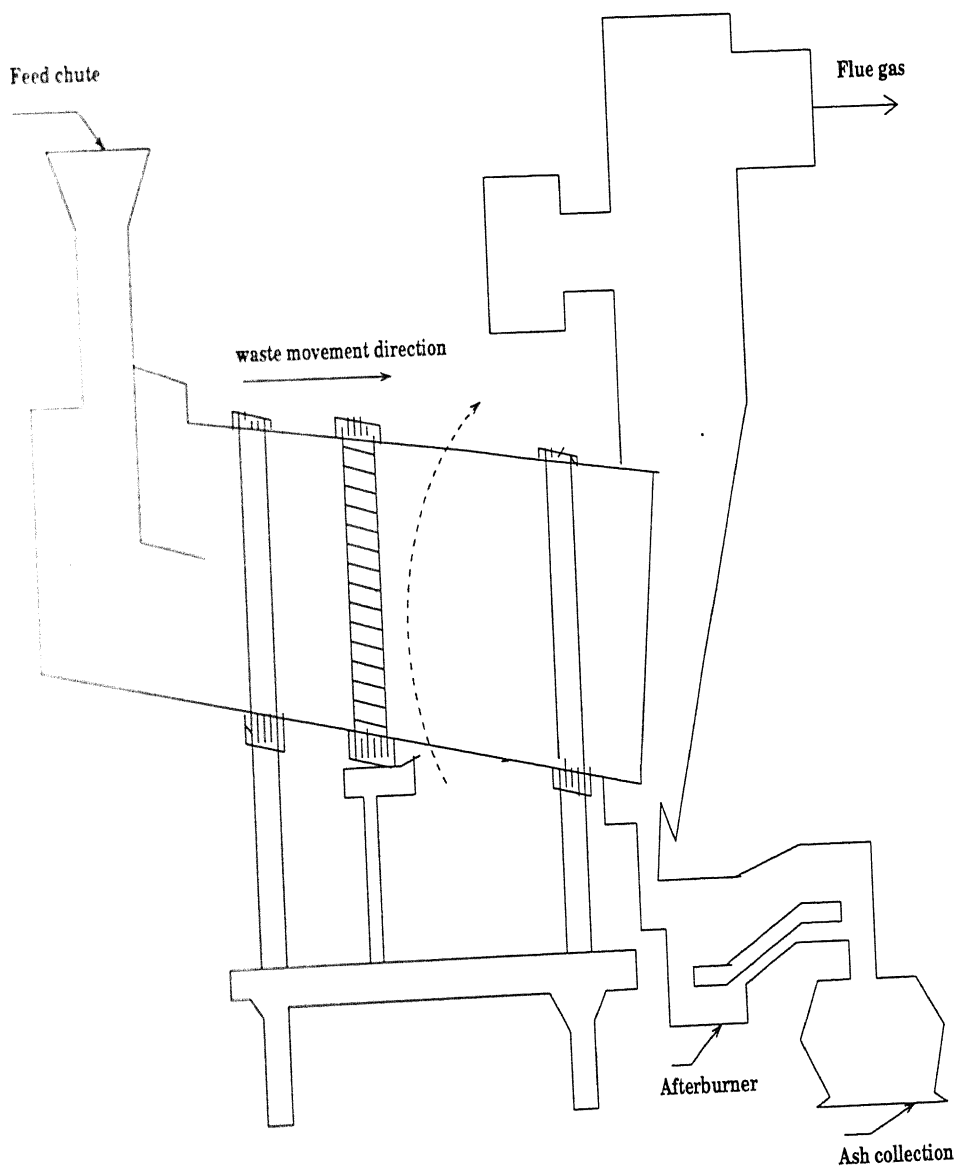


Figure 6.1: Rotary-kiln incinerator [5]

DISADVANTAGES

1. High capital costs of installation especially for low feed rates.
2. Relatively high particulate carryover to the gaseous stream.
3. Separate after burner normally required for destruction of volatiles.
4. Conditions along the kiln are difficult to control.
5. Effective kiln seal is difficult to obtain.
6. Kiln incinerators frequently get excess air due to air leakage into the kiln through the kiln end seals and feed chute. This excess air intake lowers the supplementary fuel efficiency.
7. Operation in a slagging mode to process inorganic wastes or metal drums increases kiln maintenance requirements.
8. Relatively low thermal efficiency.

6.2.2 MULTIPLE HEARTH INCINERATOR

The multiple hearth furnace is a vertical structure, a steel shell lined with refractory. The furnace interior is composed of a series of circular refractory hearths, one above the other, a rotating shaft, a series of rabble arms with teeth for each hearth, an air blower, fuel burners mounted on the walls, ash removal system and a waste feeding system.

Alternating hearths have a large annular opening between the hearth and the centre shaft. These are termed as *in-hearths*. The teeth on the rabble arms will rabble the sludge to the centre of these hearths, in toward the centre of the furnace where sludge will drop off the edge of the refractory, loading on the hearth below, an *out-hearth*.

Sludge and/or solid combustible waste is fed through the furnace roof by a screw feeder or belt and flap gate. The rotating air cooled central shaft with air cooled rabble arms and teeth plows the waste across the top hearth to the drop holes. The waste falls to the next hearth and then the next until discharged as ash at the bottom. The waste is agitated as it moves across the hearths to make sure that the fresh surface is exposed to hot gases. Figure 6.2 shows a typical multiple hearth furnace [1].

Sludge that can be processed in the multiple hearth furnace is limited in consistency to the range of 15 to 50 percent solids. With solids content below 15 percent, the sludge is more liquid than solid and will not move properly within the furnace. Such sludge tends to flow along the hearth and the rabble action will not be effective. Above 50 percent of solids, the sludge is excessively viscous and tends to plug the rabble teeth, climb up and build on the rabble arms and clog the drop holes on the out-hearth [1, 5, 10].

ADVANTAGES

1. The residence time in multiple hearth furnace is usually higher than that in the other configurations for hazardous materials having low volatility.
2. Large quantities of water can be evaporated. This is the best method for sludge with solids content 15 to 50 percent.
3. High fuel efficiency is achieved by a multizone configuration.
4. A wide variety of wastes with different physical and chemical properties can be incinerated.

DISADVANTAGES

1. Due to longer residence times of the waste material, temperature response is very slow [1].

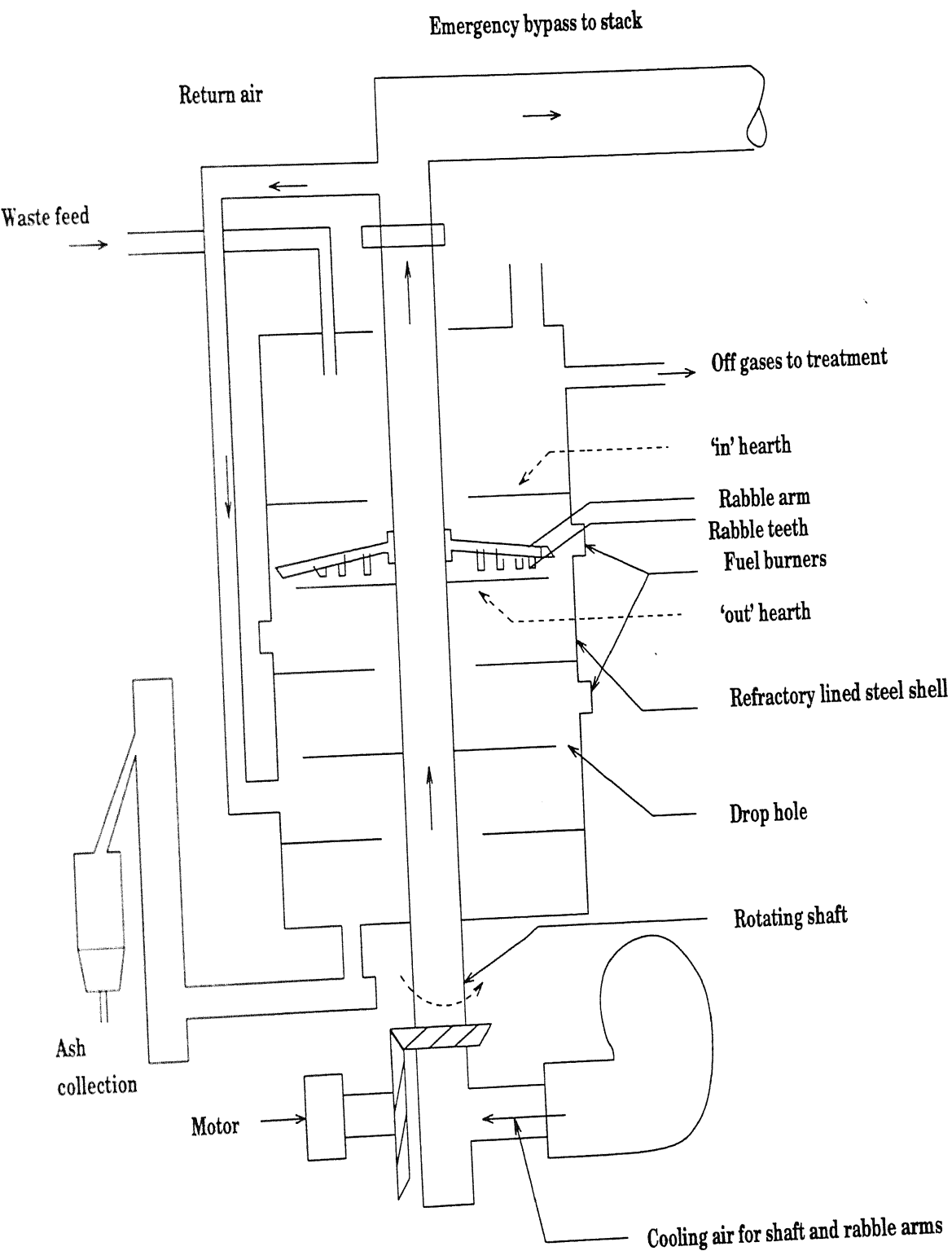


Figure 6.2: Multiple hearth furnace [1]

2. It is difficult to control the firing of the supplemental fuel because of this slow response.
3. Because of the moving parts, the maintenance costs are high.
4. These are susceptible to thermal shocks, resulting from frequent feed interruptions and excessive amount of water in the feed. These conditions may lead to early refractory and hearth failures.
5. These are not suitable for wastes containing fusible ash, wastes requiring extremely high temperatures for destruction, or irregular bulky solids since it is difficult to maintain the incinerators.

6.2.3 MULTIPLE CHAMBER INCINERATOR

Multiple chamber incinerator consists of three zones: (1) an ignition or primary combustion chamber; (2) a downward mixing chamber and (3) an up-pass secondary combustion chamber. Solid wastes are fed into the incinerator through charging doors to the grates at the bottom of the chamber. Here the wastes are dried, ignited, volatilized and oxidised into gases. Multiple chamber incinerators are generally classified as the retort type or the in-line type [10].

In the retort type incinerators, an arrangement at the bottom forces the gases to make a 90° change in the direction both on the horizontal and vertical axis. The primary and secondary reaction chambers are separated by a common wall.

The in-line chamber is distinguished by an intermediate secondary burner-mixing zone, followed by a third chamber which is a secondary combustion chamber. The combustion gases only change direction in vertical plane [10, 12]. A typical multiple chamber incinerator is shown in Figure 6.3 [10].

ADVANTAGES

1. Multiple chamber incinerators are more suitable for municipal waste than any other incinerator.
2. Solid wastes of uneven size, bulk refuse, etc., can be incinerated in multiple chamber incinerators.

DISADVANTAGES

1. Multiple chamber incinerators are generally more labour intensive than any other incineration equipment because of variations in the form of feed waste and special handling that is therefore required.
2. Inability to process liquids, gases, sludge and tar.

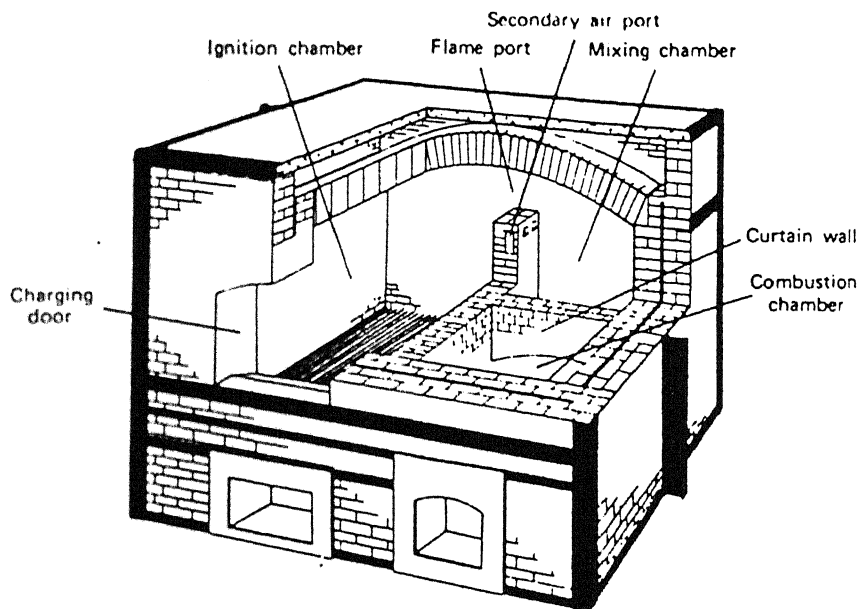


Figure 6.3: Multiple chamber incinerator (retort type)[10].

3. Temperature attained is not high enough to ensure acceptable destruction of hazardous wastes.

6.2.4 FLUIDIZED BED INCINERATOR

Fluidized bed incinerator is comprised of a vertical, cylindrical, refractory lined vessel with a perforated grid in the lower section which supports a sand bed and a gas distribution plate. The size of the solids which may be fluidized varies from less than $1\mu\text{m}$ to 10 cm ; with the best operation (most uniform) for particles between 65 mesh and $10\mu\text{m}$. Gas velocities through the beds range from 0.15 to 3 m/s (based on the empty cross sectional area: the superficial velocity). Solids or sludges are fed into the bed or onto the free board and are rapidly heated by radiation and intensive convection. The rapid heat and mass transfer result in high temperature uniformity, usually not more than a 5°C temperature differential exists between any two points of the bed. Higher velocities result in bed attrition and an increased particulate load on the particulate collection equipment. Relatively low velocity reduces pressure drop and therefore reduces the power requirement but this increases the equipment size.

Bed depth ranges from 0.4 m to several meters. Variation in bed depth affects the waste particle residence time and the system pressure drop. One therefore desires to minimize bed depth consistent with complete combustion and minimum excess air. Primary factors to be considered in specifying or designing fluidized bed incinerators are gas velocity, bed diameter, bed temperature, waste composition and characteristics [12]. A fluidized bed incinerator is shown in Figure 6.4 [12].

ADVANTAGES

1. Can handle solid, liquid, sludge and gaseous wastes.
2. Simple design with no moving parts, hence low maintenance costs.

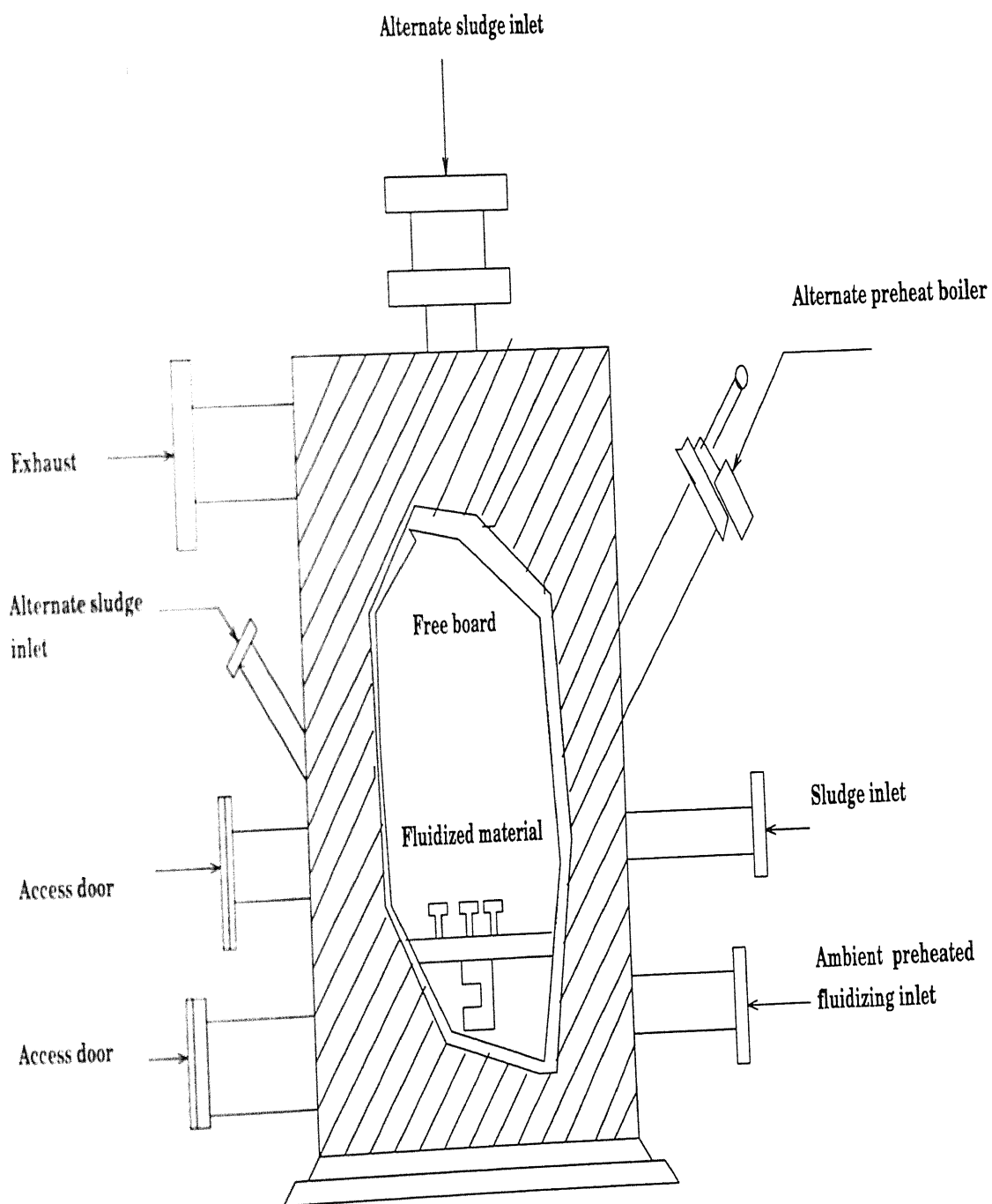


Figure 6.4: Fluidized bed incinerator [12].

3. Compact design due to high heating rate per unit volume.
4. Low gas temperatures and excess air requirements minimize nitrogen oxide formation.
5. Life of this incinerator is comparatively longer than any other type.
6. Large active surface area enhances combustion efficiency.
7. Fluctuations in feed rate and composition are easily tolerated due to the large heat capacity of the bed.

DISADVANTAGES

1. Waste should be very well pulverised else difficult to fluidize.
2. Feed selection must avoid bed damage. For example, salt laden waste should be avoided since bed agglomeration is the major problem with them.
3. May require special operating procedures to avoid bed damage.
4. Operating costs are relatively higher.
5. Incineration temperatures limited to 800°C to avoid fusing of the bed material.
6. Clinker or slag formation occurs when the feed contains a high concentration of inorganic salts which fuse to harder clinker [1, 5, 12].

6.2.5 LIQUID INJECTION SYSTEM INCINERATOR

Liquid waste combustors are flexible units to dispose of any combustible liquid waste. An important part of liquid injection system is the liquid injecting nozzle burner [5]. Liquid combustion device is essentially a suspension burner; efficient and complete combustion is obtained if and only if the waste is adequately divided or atomized and mixed with the oxygen source.

Atomization is usually achieved by mechanical means such as rotary cup or pressure atomization system or by gas fluid nozzles using high pressure air or steam. A forced draft must be supplied to the combustion chamber to produce the necessary mixing and turbulence.

Of the number of configurations available, horizontally fired units, up-fired and down-fired units are the most common types. These incinerators are suitable only for low ash liquid wastes. The exception is the down-fired design which can handle salt and particulate laden wastes. The down-fired salt unit collects the salt in molten form in the bottom of the injection chamber; these salts can be removed as molten material and quenched outside the incinerator [1, 5]. Figure 6.5 shows a liquid injection system [1].

ADVANTAGES

1. A wide-range of liquid wastes can be incinerated.
2. No continuous ash removal system is required.
3. Capable of a fairly high turn down ratio (i.e., ratio of waste converted to gases to waste fed to the incinerator).
4. Fast temperature response to changes in the waste fuel flow rate.
5. Virtually no moving parts, hence low maintenance cost.

DISADVANTAGES

1. If the waste contains solids, then burner plugging would be a major problem.
2. Flame impingement on the refractory should be prevented.
3. Very high degree of atomization of liquid waste is required.
4. It can not handle sludge with high bulk solids, since there is no ash removal system.

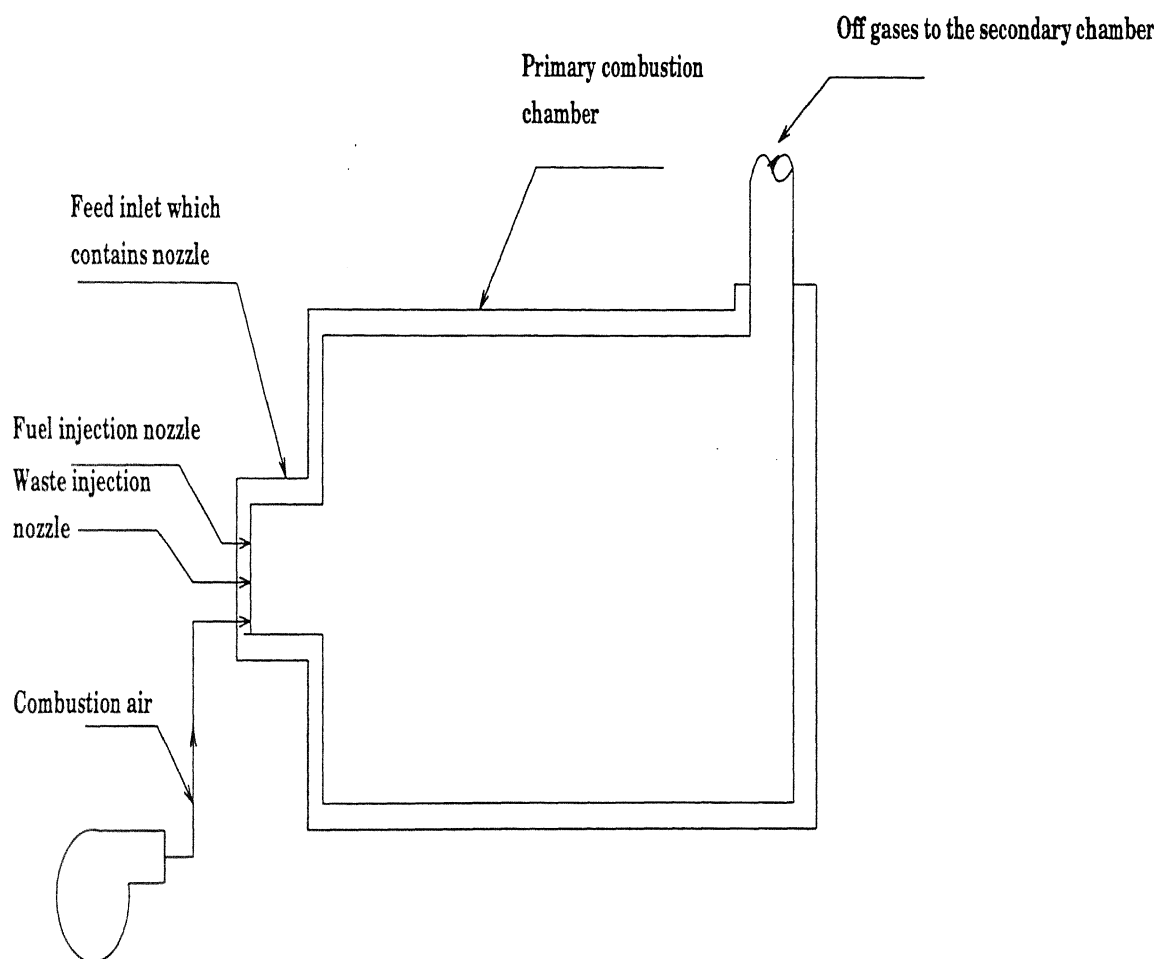


Figure 6.5: Horizontally fired liquid injection system [1].

6.2.6 INFRARED FURNACE

A typical infrared furnace system is shown in Figure 6.6 [5]. The infrared furnace system is a conveyor belt system passing through a long, refractory lined chamber. Negative draft is maintained throughout the furnace by an induced draft fan.

Combustion air (preheated) and sludge/waste travel counter to each other. Supplemental heat is provided by electric infrared heating elements within the furnace above the belt. The temperature achieved by infrared furnace is about 875°C . The conveyor belt is a continuous woven wire, high temperature alloy steel mesh that can withstand upto $1,000^{\circ}\text{C}$ within the furnace. The refractory is made up of ceramic.

Waste is fed to the belt to a depth of approximately three centimeter. The belt speed and travel is selected to provide burnout of the sludge without agitation. This feature results in relatively low level of particulate emissions. Another important feature of the infrared furnace is that low amount of excess air (approximately 20 to 30 percent only) is required. This results in a lower pressure drop in the scrubber system [5].

ADVANTAGES

1. Since there is no agitation, particulate and air emission control problems are reduced.
2. Ceramic fibre insulation, which has a very low thermal inertia, provides the ability to heat the furnace to the operating temperature in under two hours. This is a very attractive feature of this furnace, which is very useful in two shifts a day, intermittent loading and batch plants.
3. Electrical heating reduces the flue gas amount when compared to the conventional fossil fuel addition systems.

DISADVANTAGES

1. Electric energy approximately costs four times the fossil fuel on a heat value basis.

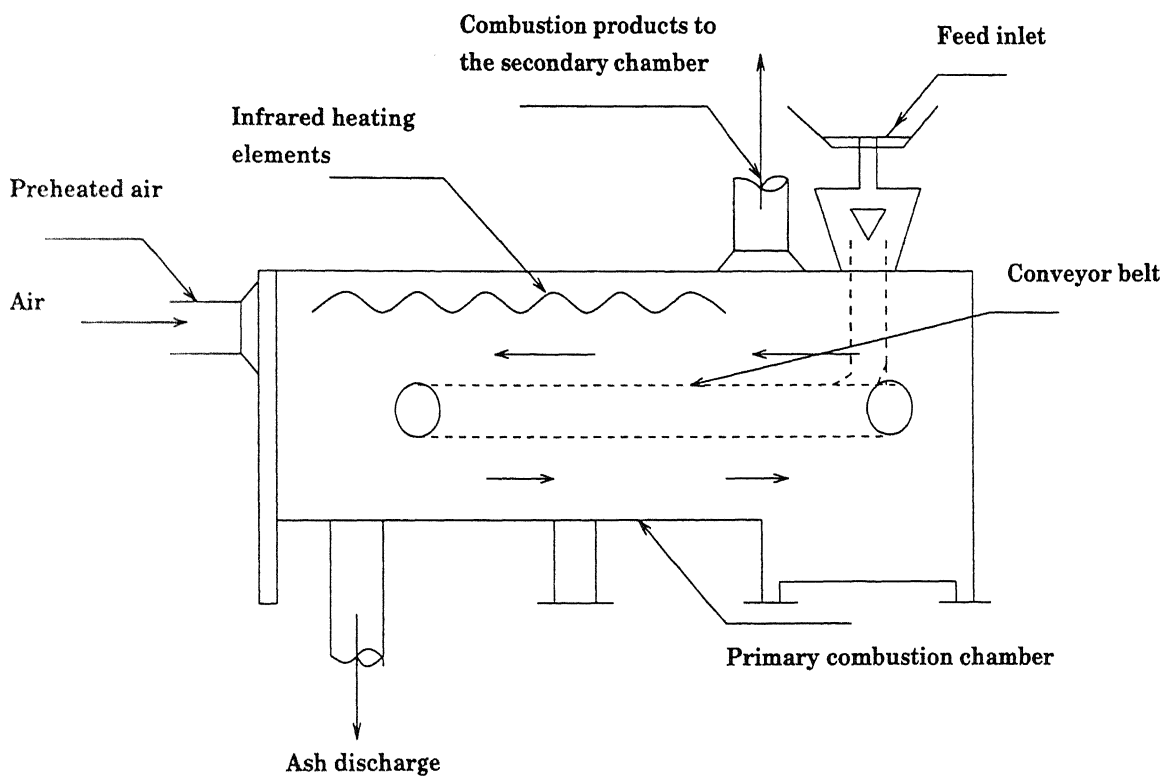


Figure 6.6: Infrared incinerator [5].

Unless the sludge will burn autogenously, an electric furnace may not be cost effective.

2. Installation costs are very high.
3. Highly corrosive gases produced during combustion may corrode the heating elements. Hence, very high corrosion resistant materials should be employed.

6.2.7 OPEN-PIT INCINERATOR

Open-pit incineration is the burning of waste materials on open land without the use of an enclosed combustion equipment. This form of incineration is utilised mainly for the disposal of explosive wastes. It is generally unacceptable for the disposal of other types of wastes because of the associated lack of combustion product effluent control.

The open-pit incinerator was originally developed by DuPont for the safe disposal of nitro cellulose which presents an explosion hazard in a conventional closed incinerator. This incinerator has an open top and an array of closely spaced nozzles that create a rolling action of high velocity air over the burning zone. Very high burning rates, long residence times leading to complete combustion and high flame temperatures are achieved. Oversized wastes, plastics and rubber that create problems in conventional incinerators are easily destroyed in the open-pit incinerators [1].

ADVANTAGES

1. Explosive wastes can be destroyed safely.
2. Highly suitable for plastics, rubber and over sized wastes.

DISADVANTAGES

1. Lack of confinement of combustion products.
2. No way to clean exit gases.

6.3 CAPITAL AND OPERATING COSTS OF AN INCINERATOR PLANT

6.3.1 CAPITAL INVESTMENT COST OF AN INCINERATOR PLANT

Initial investment for an incinerator system will include the following:

- Incineration system

Waste preparation, storage and handling:

1. Waste pretreatment equipment (e.g.: size reduction equipment, compaction equipment, filtration equipment, etc.).
2. Storage containers, tanks, transportation vehicles and containers.
3. Piping, ducts and conveyors.
4. Waste analysis laboratory, equipment, etc.
5. Waste feeding equipment (e.g.: waste conveyors, cranes, etc.).
6. Waste receiving system, waste weighing, etc.

- Incinerator

1. Incineration furnace.
2. Furnace internals (e.g.: grates, hearths, firebricks, etc.).
3. Refractory.
4. Secondary combustion chamber.
5. Nozzles, burners, etc.

6. Blowers, compressors and fans.
7. Standby equipment.
8. Motors to drive rabble arms, rocking or traveling grates.
9. Heat recovery equipment and accessories associated with them.
10. Insulation material for primary chamber, secondary chamber, heat recovery system, piping, etc.
11. Air pollution control equipment (e.g.: cyclone separator, ESPs, gas scrubbers, etc., and auxiliary equipment associated with them).
12. Ash recovery system, fly ash recovery system, sludge handling system, etc.
13. Stacks.
14. Process monitoring and control equipment (e.g.: temperature sensors, pressure sensors, etc.).
15. Continuous emission monitoring and control equipment.
16. Safety equipment.
17. Maintenance equipment.
18. Buildings, roadways, parking places and sanitary facilities.
19. Landfills for residue and sludge disposal.
20. Waste water treatment section.
21. Regeneration unit for catalyst used in afterburners.

Nonequipment expenses:

1. Land costs.
2. Spare parts inventory.
3. Operator and other personnel training facilities.
4. Permits/licenses from pollution control board or regulatory authorities.
5. Consulting charges.
6. Equipment fabrication, assembling and erection costs.

6.3.2 OPERATING COST OF AN INCINERATOR PLANT

Operating cost of an incinerator will include the following:

1. Electricity/fuel costs.
2. Transportation of waste to the incinerator plant and ash/sludge to the landfill area.
3. Ash/sludge disposal cost at the landfill.
4. Waste, fuel, ash and sludge handling, loading and unloading costs.
5. Periodic, preventive and predictive maintenance costs.
6. Air pollution monitoring and control costs (e.g.: scrubbing solution, its preparation, pumping, etc.).
7. Compliance with regulations and maintenance of all relevant records.
8. Employee salary and overheads.
9. Training public living nearby, mock drills, etc.
10. Public liability insurance costs.

11. In case of accidents, or toxic gaseous products release, etc., compensation to be paid, litigation proceedings and costs associated therein.
12. Allaying public fear about the particular plant by advertisement as well as building community relations.

The cost of money (interest or loan) can be a big factor too. Grants and zero or low interest loans will stimulate incinerator use.

6.4 SELECTION OF AN INCINERATOR

Depending upon the characteristics of the wastes, during the design stage itself, suitable type of incinerator should be selected. Economic factors would of course play a significant role in the selection of the particular type of equipment. Selection of a suitable incinerator for a particular type of a waste is given in the Figure 6.7.

Incinerator type Waste type	Rotary-kiln incinerator	Multiple hearth incinerator	Multiple chamber incinerator	Fluidized bed incinerator	Liquid injection incinerator	Infrared incinerator	Open-pit incinerator
Gaseous	Suitable but atomization is required.	Not suitable.	Not suitable. Requires large excess air.	Suitable.	More suitable than any other method.	Suitable. Turbulence is very less. hence, not preferred.	Not suitable. Open system is not acceptable.
Liquid	Same as above.	Not suitable. Liquid movement improper.	Same as above.	Suitable.	The best. Atomization helps in complete comb.	Suitable. Turbulence is less. Liquid injector is preferred.	Not suitable.
Pulvarised	Suitable next to fluid bed type.	Suitable.	Suitable but not cost effective.	Suitable.	Not suitable. Major problem is plugging.	Suitable.	Not suitable.
Sludge (5% of solids)	Suitable.	Suitable. Waste movement improper.	Same as above.	Bed agglomeration is the major problem.	Suitable if solids do not plug the nozzles.	Suitable for all sludge. Equipment cost is very high.	Not suitable.
Sludge (>5-15% of solids)	Suitable	Same as above.	Same as above.	Suitable. Problems: caking and bed agglomeration.	Not suitable because of plugging.	Same as above.	Not suitable.
Sludge (>15-50% of solids)	Suitable. solids buildup should be avoided.	The best suitable incinerator.	Same as above.	Same as above.	Not suitable.	Same as above.	Not suitable.
Sludge (>50% of solids)	Suitable. Problems: caking, erosion & buildup.	Waste too viscous and movement improper.	Best type for viscous and uneven size.	Same as above.	Not suitable.	Same as above.	Not suitable.
Explosives	Not suitable	Not suitable.	Not suitable.	Not suitable.	Not suitable.	Not suitable.	The best suitable and cost effective.

Figure 6.7: Incinerator selection guidelines

Chapter 7

DESIGN OF INCINERATORS

Keep it simple;
As simple as possible;
But no simpler.

Albert Einstein.

Wastes generated from the industrial activities have been defined as hazardous wastes if they fall under any of the 18 categories as defined under the Hazardous Waste (Handling & Management) Rules, 1989. National Waste Management Council Document, 1990, by the Ministry of Environment and Forest, Government of India, defines hazardous waste as follows: “Any waste other than radioactive waste, which by reasons of physical and/or chemical or reactive or toxic, explosive, corrosive or other characteristics causing danger or likely to cause danger to health or environment, whether alone or when coming in contact with other wastes or environment” [6].

7.1 INCINERATOR DESIGN CONCEPTS

Various steps involved in the design of incinerators are listed below. Then each one is discussed.

1. Do the proximate and ultimate analysis of the waste.

2. Characterise the waste.
3. Select suitable pretreatment and feeding mechanism.
4. Find the heating value of the waste (experimental or Dulong approximation method).
5. Get various rate expressions available for waste constituents' destruction.
6. Find out the amount of excess air to be used.
7. Find out the energy released. Operate at a reasonable retention time and temperature for wastes and gases.
8. Find out the temperature attained by the gases. With the selected residence time find whether the temperature is acceptable for the destruction of the waste.
9. If the temperature attained is not above the minimum necessary, add auxiliary fuel to increase it. Find out the amount to be added.
10. Select suitable incinerator type for the destructions of the waste. With the help of mass and energy balances, size up the chamber(s).
11. Use appropriate design equations.
12. Design suitable ash removal and disposal system.
13. Get the exit gas composition.
14. Design air pollution control systems, emission monitoring systems, stack, etc.

Incinerator design concepts are summarised in Figure 8.

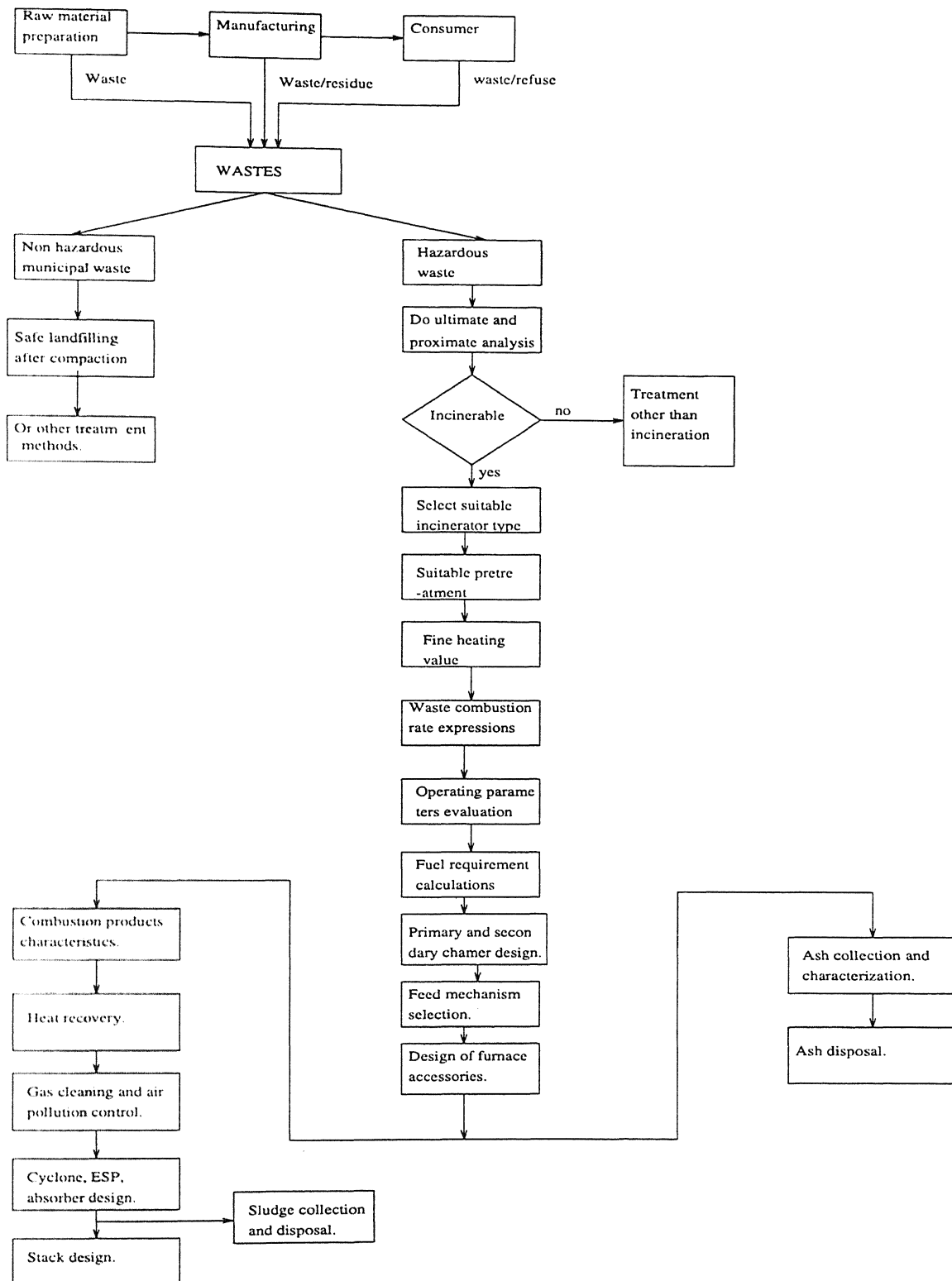


Figure 7.1: Incinerator design concepts

7.2 PROXIMATE AND ULTIMATE ANALYSIS OF WASTE

7.2.1 PROXIMATE ANALYSIS

In proximate analysis the following are determined [5]:

- Moisture
- Volatile matter
- Fixed carbon
- Ash

7.2.2 ULTIMATE ANALYSIS

It is very important to know the elemental constituents of the waste in order to determine the products of combustion and incomplete combustion (PICs) of the waste, air requirements and nature of the off-gases (composition, temperature, corrosive properties, etc.). An ultimate analysis is a standard procedure used for the determination of the elemental constituents. In this procedure, the following element fractions are usually determined.

- Carbon
- Hydrogen
- Sulfur
- Oxygen
- Nitrogen
- Halogens (chlorine, bromine, etc.)
- Heavy metals (mercury, lead, arsenic, etc.)

- Other elements that can affect the combustion process.

In addition to the components, analyses may also be performed for the presence of certain components that might be in the waste, such as hazardous constituents, PCBs, dioxins and other organics. ASTM Standard D3176 describes the standard method for performing an ultimate analysis [5].

7.3 HEATING VALUE DETERMINATION

The quantity of heat released when a waste is burnt is known as the heating value of the waste. Because combustion reactions are exothermic, all organic wastes have some finite heating value. When an organic waste exhibits a low heating value, it is usually due to high concentrations of moisture & halogenated compounds.

Heating values are expressed in terms of 'higher heating values' or 'lower heating values'. Higher Heating Value (HHV) includes the heat of condensation of water formed in the combustion reaction. Lower Heating Value (LHV) is obtained by subtracting the energy necessary to vapourize any moisture initially present in the waste. It is also known as the Net Heating Value (NHV).

The heating value of a complex waste mixture is difficult to predict *a priori*. Therefore these values should be measured experimentally. NHV and HHV are related as follows:

$$NHV = HHV - 1050(H_2O + 9(H - Cl/35.5 - F/19)) \quad (7.1)$$

where H_2O , Cl , F are weight fractions respectively of water, chlorine and fluorine present in the waste [1].

Heating values are experimentally measured. If the observations of the values are not satisfactory then Dulong's approximation method could be used. Both are described below.

7.3.1 HEATING VALUE MEASUREMENT

A representative sample of one gram from the waste is taken in an oxygen bomb calorimeter. The waste is ignited in an enclosed atmosphere of pure oxygen by an electric wire. The heat of combustion of the sample heats a water bath surrounding the bomb. The temperature rise of water is measured and the heat of combustion is calculated from this temperature increase.

A sample as small as one gram will not be a representative sample of the waste, considering the fact that the waste could be heterogeneous mixture of solids, liquids or sludge. Hence the value obtained would not also be an exact value. Hence, for such cases, larger sized samples should be used (if the bomb calorimeter of the right size is available) and/or several samples be taken and a conservative value chosen based on the results obtained.

7.3.2 DULONG'S APPROXIMATION

Dulong's approximation method can be used as a rough approximation of the heating value of carbonaceous materials. This is only an approximation and it should be used only when other means of calculations do not appear satisfactory [5, 21].

$$NHV = 14000m_C + 45000(m_H - 0.125m_O) - 760m_{Cl} + 4500m_S \quad (7.2)$$

where m_C , m_H , m_O , m_{Cl} , m_S are mass fractions of carbon, hydrogen, oxygen, chlorine and sulfur respectively [21, 22]

The available heat at any temperature T ($H_{\Delta T}$), is the gross heating value minus the amount of heat $\sum \Delta H$, required to take the product(s) of combustion from the reference temperature to that temperature T [1]. Thus

$$H_{\Delta T} = HHV - \sum \Delta H \quad (7.3)$$

7.4 TURBULENCE

Temperature, oxygen and residence time requirements for waste destruction all depend to some extent on the degree of mixing achieved in the combustion chamber. Many of the problems involved in interpreting the combustion data relate to this difficulty in the incinerators.

By properly arranging the nozzles in the incinerators, turbulence can be increased (e.g.: roof air nozzles, tangential flow of air into the burner, etc.). Turbulence can also be increased by installing baffles in the secondary combustion zone incinerators that abruptly change the direction of gaseous flow. However, this also increases the pressure drop across the system.

7.5 RESIDENCE TIME

In addition to temperature and excess air, residence time is a key factor affecting the extent of combustion. This is also known as the dwell time or the retention time. It is defined as the mean length of time the waste is exposed to the high incinerator temperatures. It is important in designing and evaluating incinerators because a finite amount of time is required for each step.

Residence time requirements increase as combustion temperature is decreased, as mixing is reduced and/or as the size of the discrete waste particles is increased. Typical residence time in liquid injection incinerators ranges from 0.5 to 2.0 seconds [1, 13]. Combustion gas residence time also lies in the range of 0.5 to 3 seconds [5]. Gas residence times are defined by the following relation:

$$\Theta = \int_0^V dV/q \quad (7.4)$$

where

Θ = mean residence time, s;

V = combustion chamber volume; and

q = gas flow rate, m^3/s , within the differential volume.

Gas flow is a function of the amount of excess air used, the temperature at that point, the extent to which the combustion reactions are completed at that point. Therefore we need a temperature profile, excess air profile and waste conversion profile along the combustion chamber. This detailed information can rarely be determined with a reasonable degree of accuracy. As an alternate approach, the flow rate q is specified at the desired operating temperature and total excess air rate. Then residence time is calculated as follows:

$$\Theta = V_E/q_{out} \quad (7.5)$$

where

V_E = volume through which the combustion gases flow after they have been heated to the desired operating temperature; and

q_{out} is the volumetric flow rate of the gases at the exit of the incinerator.

An upper bound residence time can be estimated by

$$\Theta = V_T/q_{out} \quad (7.6)$$

where V_T is the total volume of the chamber.

For most of the hazardous organic constituents, the residence time lies in the range of 0.5 to 3 seconds in the temperature range of 750 to 1,000°C, for the pyrolysis (combustion in an oxygen deficient atmosphere) mode of destruction [1, 12].

7.6 TEMPERATURE

The following factors should be ensured before deciding proper operating temperature:

1. The temperature should be high enough to heat all the waste components and intermediates above their ignition temperature to maintain combustion.

2. It should be high enough for complete reactions to occur in the specified residence time.
3. If the temperature is too high (e.g.: $1,500\text{--}2,000^{\circ}\text{C}$), then reduce the temperature and increase the residence time. This has to be done because at high temperatures corrosion rate, auxiliary fuel requirements, etc., are very high.

Theoretical determination of temperature and residence time do not give correct values because they do not take into account the formation PICs, soot, etc. Therefore, a reasonable alternative is an examination of temperature-residence time combinations used to destroy the same or a similar waste in a similar or identical incinerator.

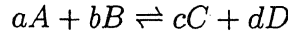
Usually 750°C is the minimum temperature needed to avoid smoke formation. A more typical hazardous waste incinerator temperature is $1,000^{\circ}\text{C}$. Halogenated aromatic wastes require $1,200^{\circ}\text{C}$ or higher temperature for complete destruction and to ensure that the PCBs formation is within the acceptable limits [5]. For example, in PCBs incineration a destruction efficiency of 99.9999% should be achieved.

Temperature varies from one point to another in the combustion chamber, being the highest in the flame and lowest at the refractory wall or at a point of significant air infiltration. So, the point where the combustion temperature is measured is very important to know. Ideally the temperature should be measured in the bulk gas flow at a point after which the gas has traversed the combustion chamber volume that provides the specified residence time for the unit. It should not be measured at a point of flame impingement, at the refractory wall, or directly in sight of thermal radiations from the flame [13]

7.7 CHEMICAL REACTION EQUILIBRIUM

Thermodynamic analysis shows that the extent of reaction of the ideal gases (a realistic assumption at combustion temperatures) is given by the equilibrium constant K_P , which

is a function only of the temperature. The equilibrium constant for the reaction



is given by

$$K_P = \frac{p_C^c * p_D^d}{p_A^a * p_B^b} = \frac{[C]^c * [D]^d}{[B]^b * [A]^a} \quad (7.7)$$

where p_i and $[i]$ represent partial pressure and concentration of component 'i'.

For combustion calculations, several reactions worthy of consideration in evaluating heat and mass flows, especially the gas phase reactions of H_2 , H_2O , CO , CO_2 , O_2 with H_2 , CO_2 and O_2 should be considered. Equilibrium considerations under conditions near to stoichiometric may indicate that substantial nitrogen oxides and carbon oxides may also be generated. Various possible combustion reactions for carbon, nitrogen, oxygen and sulfur reactions are summarised and a detailed discussion and charts showing the equilibrium constant values as a function of temperature can be found in the reference [12]. These equations are applicable when reactions are taking place as indicated. But in practical combustion processes, initially the organic matter forms intermediate products and these products subsequently produce the end products like CO_2 , SO_2 , etc. Therefore it becomes very difficult to calculate the equilibrium constants for various reactions since the number of components and the number of intermediates are very high.

Because of these complexities, in the incinerator design calculations, a very high temperature is provided and complete combustion reaction conditions are maintained by providing excess air, increased residence time, good turbulence, etc.

7.8 EXCESS AIR

The maximum furnace temperature in any combustion process is obtained when the fuel and waste are supplied with theoretical amount of oxygen required. The temperature attained by the flue gases at these conditions with perfect insulation is known as the

adiabatic flame temperature [23]. For practical reasons, instead of oxygen air is supplied for burning [10].

Air is supplied for combustion in excess of that theoretically required for complete combustion (oxidation). The excess air is normally determined from Orsat analysis of the combustion products, the formula being

$$\text{excess air percent} = \frac{100 * O_2}{(0.264N_2 - O_2)} \quad (7.8)$$

For most incinerators with the all-refractory furnaces, normally used excess air percent varies from 50 to 200 percent. To ensure complete combustion we must provide excess air, at the same time excess air should not be too low or too high since PICs formation is more at low excess air and fuel requirement is high at high excess air. Determination of the excess air percent strongly depends on the furnace temperature, inlet temperature of air, moisture content of the waste, turbulence in the system, net heat release of the waste, etc.

Figure 7.2 shows excess air percent as a function of furnace temperature and moisture content of the waste [10]. This can be used for the design of the incinerator system to find the excess air percent for a waste whose percent moisture content and desired destruction temperatures are known.

Figure 7.3 shows excess air percent relation with net heat release rate and furnace temperature [10].

7.9 AUXILIARY FUEL

Depending on the composition of the waste and the type of the waste (solid, liquid, gas or sludge), moisture content of the waste, the net heating value (NHV) may vary. Some wastes are termed as autogenous, some are not. If the self combustion of the waste brings the temperature of the combustion products above the destruction temperature desired, then they are termed as autogenous. In these cases excess amount of heat can be recovered

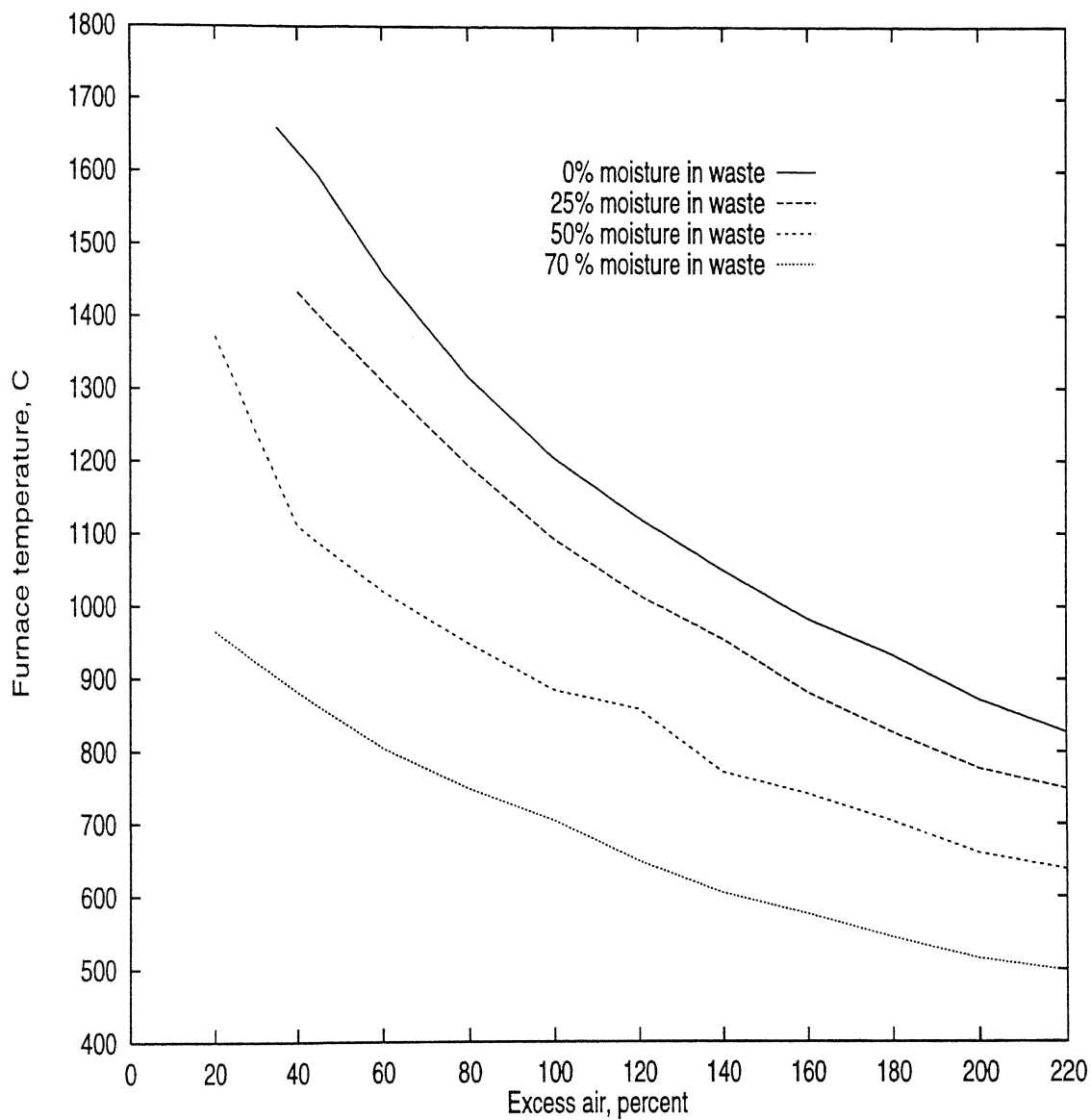


Figure 7.2: Excess air percent determination [10].

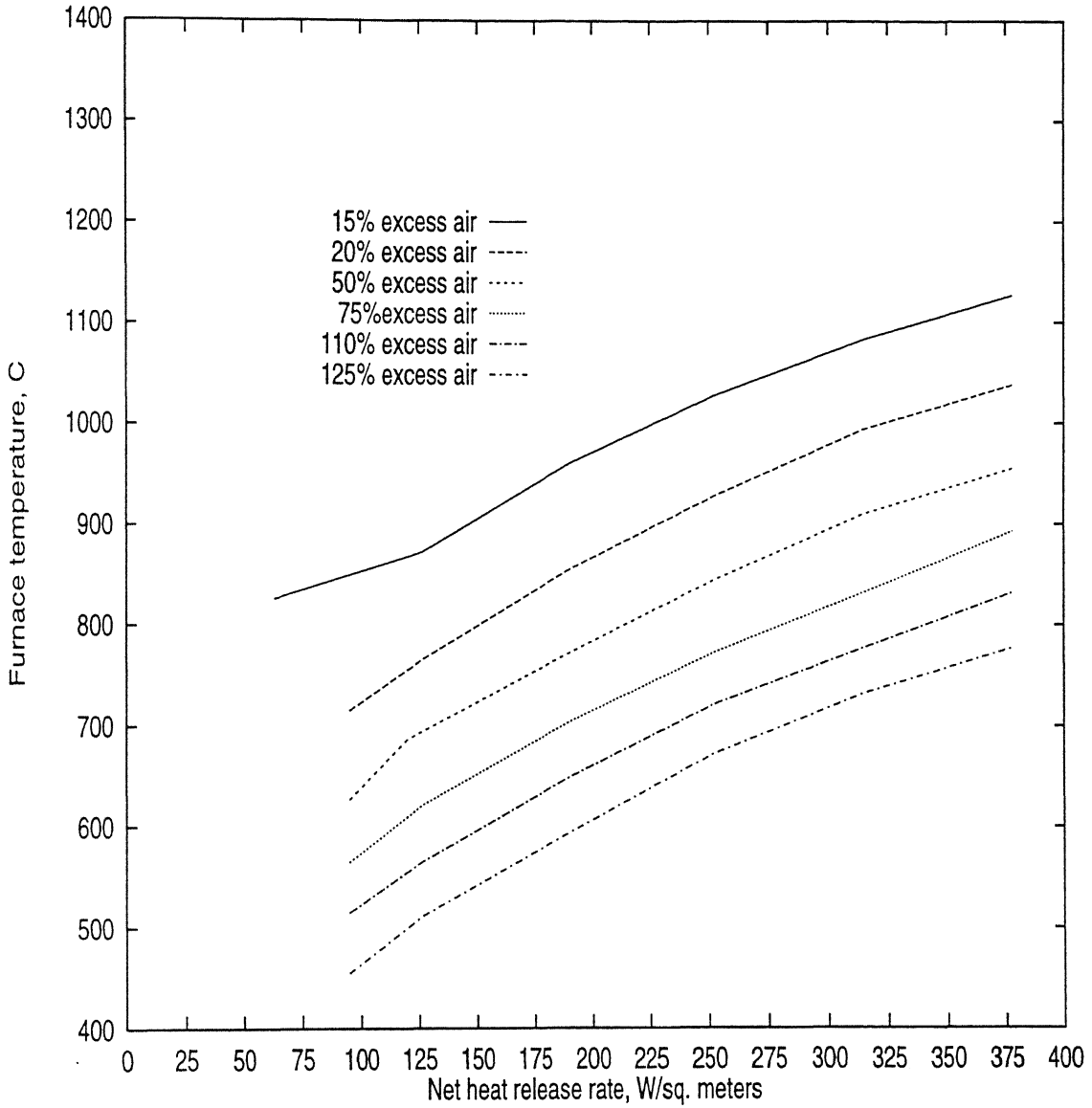


Figure 7.3: Excess air on the basis of heat release rate and temperature [10].

through waste heat boilers, or can be used to preheat the combustion air. If the temperature attained by the combustion product gases is below the desired destruction temperature, it has to be increased by addition of auxiliary fuel. The exact amount of fuel to be added can be found from detailed energy balances. The auxiliary fuel should be divided properly between the primary and secondary chambers [5, 21].

7.10 ELECTRIC HEATING

Adding fuel to the furnace requires air for its combustion which increases the amount of combustion products, PICs and the treatment costs involved. Alternatively, if we could maintain the temperature inside the furnace by means of electric heating, it would be of great help. It has serious disadvantages also.

7.10.1 DISADVANTAGES OF ELECTRIC HEATING

1. In terms of heat value, electricity is approximately four times costlier than conventional liquid fuels [5].
2. Highly corrosive gases may be produced in the furnace (e.g.: HCl , SO_3 , etc.). This requires very high corrosion resistant materials or additional preheater section. This may increase the initial investment costs.
3. For electrical heating we should have uninterrupted power supply which is very difficult in many places in India.

We can have electrical system heating as a backup medium or in combination with the conventional fuel injection systems. Pulverised coal, liquid and gaseous fuels can also be used as auxiliary fuel. A detailed determination of auxiliary fuel requirements is given in the present design problems.

7.11 SECONDARY COMBUSTION CHAMBERS

Secondary combustion chambers are simple combustors to destroy (by oxidation) the gaseous hydrocarbons and PICs not destroyed in the primary combustion chamber. These are also termed as after burners. Three types of after burners are described here: (1) direct flame, (2) thermal and (3) catalytic.

7.11.1 DIRECT FLAME AFTERBURNERS

In direct flame afterburners a high percentage of gases pass directly through the flame.

7.11.2 THERMAL AFTERBURNERS

In thermal units the gases will remain in a high temperature oxidizing atmosphere long enough for oxidation reactions to take place. Thermal afterburners are usually an integral part of rotary kilns used in hazardous waste incinerators. Temperatures ranging from 650 to 1300°C are generally required to destruct the wastes completely [1, 10]. The following temperature ranges are often used as guidelines:

To oxidize hydrocarbons: 500 to 650°C

To oxidize carbon monoxide: 650 to 800°C.

To destruct PCBs and dioxins: 1,000 to 1,300°C

Residence time in the secondary combustion chambers range from 0.2 to 2.0 seconds except in cases of PCBs and dioxins it may be as high as 6.0 seconds [24].

ADVANTAGES OF THERMAL AND DIRECT FLAME SYSTEMS

1. Complete combustion is achieved in both the cases. Possibility of heat recovery exists.
2. Allows more flexibility in incinerator operation.

DISADVANTAGES

1. Fuel requirements are very high.

7.11.3 CATALYTIC AFTERBURNERS

Catalytic afterburners incorporate a catalytic surface to accelerate the oxidation reactions. Residence time for catalytic operation is typically about one second. Catalytic afterburners are used for gaseous wastes containing very low concentrations of combustible materials and air [1, 24].

ADVANTAGES

1. Combustion reactions can be carried out at relatively lower temperatures, which is more economical to operate than other afterburners.
2. Off-gases produced are well suited for waste heat recovery units.

DISADVANTAGES

1. Catalytic systems are susceptible to poisoning agents, activity suppressants and fouling agents.
2. Frequent replacement of catalyst increases the cost of operation.
3. Catalyst burnout occurs at high temperatures (800°C or above).

7.12 AIR NOZZLE SYSTEMS

Nozzles are used to inject air and fuel into the incinerators. These nozzles can be classified as (1) underfire, (2) overfire and (3) side jet nozzles.

Research data dating back to 1951 (Bituminous Coal Research, Inc, BCR, Aid to industry 500-300 revision of technical report No.7 [1]), show that maximum combustion efficiency is obtained with air jets located inside or in the end walls of various furnaces, only a few centimeters above the fuel bed, supplying the combustion and excess air to the portion of the flame characterised by maximum luminosity and maximum radiation heat transfer. It has also been observed that air jets located high above the fuel bed have a chilling effect on furnace gases after the flames have lost their luminosity [13].

The furnaces are usually provided with underfire and side fire nozzles. Under fire nozzles increase the turbulence between solid waste particles and gases. But this increases the particulate carryover also.

Numerous visual tests and some dust loading and gas analysis tests by Wisconsin Chemical & Testing Company [13] performed on a number of industrial incinerator installations showed that a proper side air distribution can provide a smokeless operation. This is due to almost complete combustion within the furnace itself, shortening of flame, practically uniform temperature in all parts of the furnace and reduction or elimination of slag [1, 13]. In an attempt to provide turbulence and mixing of air with the flame, roof air nozzles had been introduced. However, they are not currently much in vogue.

7.12.1 UNDESIRABLE EFFECTS OF ROOF AIR NOZZLE SYSTEM

1. Extreme temperatures in some parts of the furnace.
2. Penetration of air jets into the refuse bed.
3. Impingement of flame on furnace walls due to air jets adjacent to side walls.

The above conditions result in localized high temperature burning rates and in some cases penetration of the air jets and entrained flame below the grates.

The effects of high temperatures on the furnace walls, localized high burning rates, flame impingement on the refractory enclosures, as well as the effect of the flame heat penetration below the grates on the mechanical equipment are highly undesirable.

7.13 DESIGN A: DESIGN OF GRATE FURNACE INCINERATORS

7.13.1 WASTE CHARACTERISTICS

CPCB Waste Category no: 12 Toxic organics

Composition (weight %)

Water content	= 35%;
Non-combustibles, non-volatile and ash content	= 15%;
Carbon	= 30%;
Hydrogen	= 5%;
Sulfur	= 5%;
Nitrogen	= 3%;
Chlorine	= 3%;
Oxygen	= 4% ;
Mass flow rate of the waste	= 2,000 <i>kg/hr</i> .

The waste characteristics are based on the Executive summary [6] and General Electric company's solid waste technology assessment [25].

NET HEATING VALUE CALCULATIONS

By Dulong's approximation method[21]:

$$\begin{aligned}
 \text{Net heating value} &= 14,000m_c + 45,000(m_H - 0.125m_o) - 760m_{Cl} + 4,500m_s \\
 &= 14,000(0.3) + 45,000(0.05 - 0.125 * 0.04) - 760(0.03) + 4,500(0.05) \\
 &= 6425 \text{ Btu/lb of waste} \\
 &= 14945 \text{ kJ/kg of waste} \\
 \text{Bulk density of the waste} &= 900 \text{ kg/m}^3
 \end{aligned}$$

TEMPERATURE OF DESTRUCTION

$$\begin{aligned}
 \text{In the primary chamber} &= 900^\circ\text{C} (1652^\circ\text{F}) \\
 \text{In the secondary chamber} &= 1,000^\circ\text{C} (1,832^\circ\text{F})
 \end{aligned}$$

RESIDENCE TIME

$$\begin{aligned}
 \text{Residence time in the primary chamber} &= 2 \text{ s} \\
 \text{Residence time in the secondary chamber} &= 1.5 \text{ s}
 \end{aligned}$$

EXCESS AIR REQUIREMENT

From Corey[10], for a temperature of $1,000^{\circ}\text{C}$ and moisture content of 35%, required excess air percent is 90.

FUEL OIL CHARACTERISTICS

Fuel oil characteristics are given below [5]:

Fuel used	= Fuel oil;
GHV of fuel	= $45,125 \text{ kJ/kg}$ ($19,400 \text{ btu/lb}$);
NHV of fuel	= $20,380 \text{ kJ/kg}$ @ 30% excess air and $1,000^{\circ}\text{C}$
Density of fuel oil	= 864 kg/m^3
Elemental composition of fuel oil:	
Carbon	= 87.5%;
Hydrogen	= 12.5%;
Excess air used for fuel oil burning	= 30%;

7.13.2 MATERIAL BALANCE

Flow rate of waste to be incinerated	= $2,000 \text{ kg/hr}$ ($4,405 \text{ lb/hr}$)
Moisture present in the waste	= 35% (wt percent)
Moisture in the waste	= $2,000 * 0.35$ = 700 kg
Dry feed:	
Dry feed	= waste fed - moisture = $2,000 \text{ kg/hr} - 700 \text{ kg/hr}$ = $1,300 \text{ kg/hr}$
Non-combustibles and ash content	= 15%
Ash from waste combustion	= $2,000 * 0.15$ = 300 kg/hr
Combustible materials content	= total feed - moisture content - ash content = $2,000 - 700 - 300$ = $1,000 \text{ kg/hr}$
Heating value of the waste (net)	= $14,945 \text{ kJ/kg}$ ($6,425 \text{ Btu/lb}$)
Total heat content of the waste	= $2,000 * 14,945$ = 29.89 GJ/hr

COMBUSTION CALCULATIONS

Component present by weight percent (from elemental analysis):

$$\begin{aligned}
 C &= 30\%; \\
 H_2 &= 5\%; \\
 N_2 &= 3\%; \\
 O_2 &= 4\%; \\
 S &= 5\% \\
 Cl_2 &= 3\%;
 \end{aligned}$$

The temperature, residence time and excess air rate are selected in such a way that complete combustion, DRE (destruction and removal efficiency) greater than 99.9% is ensured.

(1) Carbon:

$$\begin{aligned}
 C + O_2 &\rightleftharpoons CO_2 \\
 \text{Carbon present in the waste} &= 600 \text{ kg} \\
 \text{Stoichiometric oxygen required} &= 600 * 32/12 \\
 &= 1600 \text{ kg/hr}
 \end{aligned}$$

Sulfur:

$$\begin{aligned}
 S + O_2 &\rightleftharpoons SO_2 \\
 \text{Sulphur present in the waste} &= 2000 * 0.05 \\
 &= 100 \text{ kg} \\
 \text{Stoichiometric oxygen required for sulfur} &= 100 * 32/32 \\
 &= 100 \text{ kg/hr}
 \end{aligned}$$

Hydrogen:

$$\begin{aligned}
 H_2 + (1/2)O_2 &\rightleftharpoons H_2O \\
 \text{Hydrogen present in the waste} &= 2000 * 0.05 \\
 &= 100 \text{ kg} \\
 \text{Stoichiometric oxygen requirement for hydrogen} &= 100 * 16/2 \\
 &= 800 \text{ kg/hr.}
 \end{aligned}$$

Chlorine:

A significant amount of chlorine is present in the waste (3%). While doing the material balance it is assumed that chlorine present in the waste is converted to HCl . When the chlorine content is more than 0.5% in the waste, considerable amount of PCBs are generated. U.S.EPA [5] has recommended a temperature of $1,000 - 1,200^\circ C$ and residence time of 2 s for the incineration of such wastes. CPCB (India) has recommended a temperature of $1,050 - 1,100^\circ C$ in the secondary combustion chamber and the residence time in the secondary chamber should be at least one second.

Chlorine balance:

$$\begin{aligned}
 Cl_2 + H_2 & \rightleftharpoons 2HCl \\
 HCl \text{ produced in the burning process} & = 2,000 * 0.03 * 73/71 \\
 & \simeq 62 \text{ kg/hr.}
 \end{aligned}$$

COMBUSTION ANALYSIS

$$\begin{aligned}
 \text{Total stoichiometric air requirement} & = 2,500 \text{ kg/hr.} \\
 O_2 \text{ requirement in terms of moles} & = 78.13 \text{ kmoles} \\
 \text{Air contains 79\% of } N_2 \text{ \& 21\% of } O_2 . & \\
 \text{Nitrogen flow rate (stoichiometric)} & = 294 \text{ kmoles/hr (8,230 kg/hr).} \\
 \text{Total stoichiometric air requirement} & = 10,730 \text{ kg/hr.} \\
 \text{Excess air of 90\% is used.} & \\
 \text{Total air required per hour of operation} & = 10,730 * 1.9 \\
 & = 20,390 \text{ kg} \\
 O_2 \text{ present in the waste} & = 2,000 * 0.04 \\
 & = 80 \text{ kg/hr} \\
 N_2 \text{ present in the waste} & = 2,000 * 0.03 \\
 & = 60 \text{ kg/hr.} \\
 \text{Moisture present in the waste} & = 700 \text{ kg} \\
 \text{Water produced in the combustion chamber} & = 900 \text{ kg/hr}
 \end{aligned}$$

From psychrometric charts [11]; for relative humidity of 50% and ambient temperature of $25^\circ C$

$$\text{Humidity} = 0.01 \text{ kg/kg of dry gas.}$$

$$\begin{aligned}
 \text{Moisture coming along with air} & = 20,390 * 0.01 \\
 & = 205 \text{ kg/hr.} \\
 CO_2 \text{ produced} & = 2,200 \text{ kg/hr.} \\
 SO_2 \text{ produced} & = 200 \text{ kg/hr} \\
 \text{Steam at the outlet} & = 1,805 \text{ kg/hr.} \\
 \text{Total air fed} & = 20,390 \text{ kg/hr.} \\
 \text{Unreacted oxygen} & = 2,330 \text{ kg/hr.} \\
 \text{Nitrogen leaving the furnace} & = 15,700 \text{ kg/hr.} \\
 \text{Hydrogen chloride produced} & = 62 \text{ kg/hr.}
 \end{aligned}$$

The above combustion analysis based on the assumption that no fuel is used. If auxiliary

fuel is used to help combustion then the analysis should include the amount of fuel and air accompanying the fuel should also be considered.

MASS BALANCE CHART

Waste fed into the furnace	= 2,000 <i>kg/hr</i>
Air fed (including moisture)	= 20,595 <i>kg/hr</i> .
Total mass into the furnace	= 22,595 <i>kg/hr</i>

The following are mass flow rate of materials leaving the secondary furnace:

<i>CO</i> ₂	= 2,000 <i>kg/hr</i>
<i>SO</i> ₂	= 200 <i>kg/hr</i>
<i>HCl</i>	= 62 <i>kg/hr</i>
Unreacted oxygen	= 2,330 <i>kg/hr</i>
Nitrogen leaving the furnace	= 15,700 <i>kg/hr</i>
Ash generated	= 300 <i>kg/hr</i>
Total mass flow rate out of the system	= 22,595 <i>kg/hr</i>

AUXILIARY FUEL FLOW RATE CALCULATIONS

In the calculations of auxiliary fuel rate, the steps involved are as follows[5]:

STEP 1:

Assume the waste is burnt autogenously (without addition of fuel). Calculate the temperature attained by the combustion products.

STEP 2:

Compare the temperature in step 1 with the desired temperature.

STEP 3:

If the temperature in step 1 is greater than the desired, then there is no need to add fuel. If the temperature is less, then calculate the amount of heat required to raise the combustion products to the desired temperature.

STEP 4:

Calculate the amount of fuel to be added.

Furnace temperature calculations:

Furnace temperature is calculated by the following relation.

$$T - t = \frac{\text{heat input}}{W_g * S_{pm}} \quad (7.9)$$

where W_g = mass, kg/hr

T = temperature attained by the combustion products, $^{\circ}K$,

t = ambient temperature, $^{\circ}K$

S_{pm} = mean specific heat of waste, (J/kg)

Heat generated is 28.3 *MBH*

28.3 *MBH* corresponds to 49,775 *lb* of combustion products.

1 *MBH* corresponds to 1,759 *lb* of combustion products. From Fig. 6.27, Corey[10], for moisture content of 35%, for refractory furnaces, the correction factor is 0.76.

$$\begin{aligned} T - t &= \frac{(\text{heat input} * \text{correction factor})}{(W_g * S_{pm})} \\ &= \frac{1 * 10^6 * 0.76}{(1,759 * 0.28)} \\ &= 1,543^{\circ}F \\ T &= 1,543 + 75 \\ &= 1,618^{\circ}F \end{aligned}$$

The furnace temperature would be $\simeq 880^{\circ}C$ ($1,618^{\circ}F$).

Since the desired temperature is $1,000^{\circ}C$, fuel has to be added to increase the temperature.

7.13.3 HEAT BALANCE

COOLING AIR FLOW RATE CALCULATIONS

In some incinerators air is circulated to pick up the heat from the process and then the air crosses the system boundary and is subsequently discharged to the atmosphere. Water quenching is also used sometimes. Since the incineration temperature is very high and

the waste heat generated is also very high, in the present design problem cooling air flow rate and quench water flow rate are not calculated. Instead, waste heat recovery methods, possibility of steam and/or electricity generation are explored. Detailed discussion and analysis are presented in the eighth chapter [1, 5].

Combustion products exit the secondary chamber at a temperature of 1000°C (1832°F)

Enthalpy of air @ $1,000^{\circ}\text{C}$ = $1,060 \text{ kJ/kg}$ (456 Btu/lb)

Enthalpy of steam @ $1,000^{\circ}\text{C}$ = $4,575 \text{ kJ/kg}$ ($1,967 \text{ Btu/lb}$)

HEAT LOSS BY ASH

The ash temperature leaving the incinerator is assumed to be 500°C . Generally heat capacity of ash can be assumed to be that of soil. From the mass flow rate of ash removed from the incinerator, heat loss can be calculated. Generally ash contains heat in proportions to its temperature [5].

Heat capacity of soil	= $0.711 \text{ kJ/kg} - \text{K}$ ($0.17 \text{ Btu/lb}^{\circ}\text{F}$)
Ash heat content	= mass flow rate of ash * specific heat of ash * temperature difference
	= $300 \text{ kg/hr} * 0.711 \text{ kJ/kg} - \text{K} * 475 \text{ K}$
	= $101,320 \text{ kJ/hr}$.
Heat loss from the system due to ash discharge	= $101,320 \text{ kJ/hr}$ (0.105 MBH)

RADIATION LOSSES FROM THE FURNACE

There are two ways of calculating the heat lost due to radiation from the furnace.

1. From the temperature at which the waste is fired and the external surface area of the furnace [5].
2. The heat loss can also be approximated by a value based on the total quantity of heat released within the chamber(s) [5].

Heat input in MBH	Expected loss from radiation
up to 15	3.00
20	2.75
25	2.50
30	2.00
40	1.75
greater than 50	1.50

In this design problem, heat input is 28 MBH. As a good approximation, the expected loss from radiation can be taken as 2.2% of the heat input.

$$\begin{aligned}\text{Heat loss by radiation} &= 29.89 \text{ MJ/hr} * 0.022 \\ &= 657,580 \text{ kJ/hr}\end{aligned}$$

Humidity is vapor and not liquid, which enters the process with combustion air. Hence a correction should be made to account for its vapourization.

$$\begin{aligned}\text{Heat of vaporization of water @ 1 atm} &= 2,256 \text{ kJ/kg} \\ \text{Humidity mass flow rate} &= 205 \text{ kg/hr.} \\ \text{Heat of vapourization is} &= 462,525 \text{ kJ/hr}\end{aligned}$$

This heat has to be subtracted from the total heat lost.

DETERMINATION OF TOTAL HEAT LOST

To determine the flue gas temperature the following are required.

1. Mass flow rate of the waste.
2. Mass flow rate of air (in) including excess air, its temperature and humidity.
3. Ash leaving the system and heat lost due to that.
4. Heat loss by radiation and other heat losses.

For the determination of flue gas temperature, the total heat lost in the operation should be calculated first.

$$\begin{aligned}
 \text{Net heat loss} &= \text{heat lost by radiation} + \text{heat lost in ash/residue} \\
 &\quad - \text{heat of vapourization.} \\
 &= 657,580 + 102,320 - 462,525 \\
 &= 287,580 \text{ kJ/hr}
 \end{aligned}$$

The net heat available to increase the flue gas to the required temperature can be calculated as follows:

$$\begin{aligned}
 \text{Net heat available} &= \text{heat content of waste} - \text{heat lost in the operation} \\
 &= 29.89 * 10^6 - 29.6375 * 10^4 \\
 &= 29.59 * 10^6 \text{ kJ/hr}
 \end{aligned}$$

DETERMINATION OF FLUE GAS TEMPERATURE

Calculation of outlet temperature, if no fuel is used, will help to find out the amount of auxiliary fuel to be added and amount of heat that could be recovered. Temperature in the incinerator will not be uniform. The temperature near the burner will be the highest in the chamber. The temperature within the chamber will vary as a function of air flow rate and direction, waste introduction, chamber geometry, residence time, turbulence, heat losses, etc [10].

A trial and error procedure is used to calculate the outlet temperature at the outlet of the incinerator. Detailed combustion analysis shows that the outlet temperature of the flue gas is 880°C.

CALCULATION OF HEAT DEFICIENCY

From Perry [11],

Specific heats of gases:

Component	C_p in cal/(gm-°C)
CO_2	0.3
O_2	0.275
N_2	0.295
SO_2	0.205
HCl	0.22
Moisture enthalpy	4575 kJ/kg

$$\text{Total heat content of the outgoing gases} = \sum_i m_i C_{p_i} \Delta T + \text{Moisture enthalpy} \quad (7.10)$$

Substituting the C_p values from the above table in to this equation, total heat necessary to bring the combustion products to 1000° is calculated

Total heat required	$= 33 * 10^6 \text{ kJ/hr.}$
Total heat available (by self combustion of waste)	$= 29.59 * 10^6 \text{ kJ/hr}$
Heat deficiency	$= 33 * 10^6 - 29.59 * 10^6$
	$= 3.41 * 10^6 \text{ kJ/hr}$

FUEL FLOW RATE CALCULATIONS

Fuel oil is used to increase the temperature.

Fuel oil properties:

Heat of fuel oil	$= 45,165 \text{ kJ/kg};$
Heat of fuel oil	$= 20,380 \text{ kJ/kg};$
Density of the waste	$= 866 \text{ kg/m}^3$
Moisture content:	
Moisture	$= 87.5 \text{ } \%$;
Hydrogen	$= 12.5 \%$;
Air required/liter of fuel oil	$= 16.16 \text{ kg}$
Gas/liter of fuel oil	$= 16 \text{ kg}$
Water generated per liter of fuel oil	$= 1.05 \text{ kg}$
Fuel oil required	$= \frac{\text{heat deficiency}}{\text{NHV of fuel oil}}$
	$= (3.41 * 10^6 \text{ kJ/hr}) / (20,380 \text{ kJ/kg})$
	$= 168 \text{ kg of fuel oil per hour}$
	$= 194 \text{ lit. of fuel per hr. of operation}$
From appendix G of Brunner [5]	
Air flow rate of combustion of fuel @ 30% excess	$= \text{air per lit. of fuel}$
	$* \text{volumetric flow rate of fuel oil}$
	$= 16 \text{ kg/lit. of fuel} * 194 \text{ lit/hr}$
	$= 3,135 \text{ kg/hr.}$
Moisture accompanying air	$= 31 \text{ kg}$
Gas generated from the combustion of fuel oil	$= 16 \text{ kg/lit. of fuel} * 194 \text{ lit. of fuel/hr}$
	$= 3,112 \text{ kg of dry gas per hour of operation}$
Moisture generated from fuel combustion	$= 1.05 \text{ kg of moisture}$
	$\text{per lit. of fuel oil} * 194 \text{ lit/hr}$
	$= 205 \text{ kg of moisture per hour}$

Heat in the gas at the outlet of the chamber is the sum of heat from combustion and heat from combustion of fuel.

Heat in the out of the gases	$= 37.13 * 10^6 \text{ kJ/hr}$
Total combustion products exiting the secondary chamber	$= 23,605 \text{ kg/hr}$
Total moisture exiting the secondary chamber	$= 1,805 + 205$
	$= 2,010 \text{ kg/hr}$
Ash exiting the primary chamber	$= 300 \text{ kg/hr}$

3.4 GRATE DESIGN

GRATING RATE (R_c)

Grating rate is the mass flow rate of waste into the incinerator grate.

Quantity of waste to be incinerated = 2,000 *kg/hr* (4,405 *lb/hr*)

GRATE LOADING (L_G)

Grate loading is the amount of waste fired per unit area of grate per hour of operation.

$$L_G = 10 \log 10 R_c \quad (7.11)$$

where R_c is refuse combustion rate, *kg/hr* (*lbs/hr*)

$$\begin{aligned} L_G &= 10 \log_{10} 4,405 \\ L_G &= 180 \text{ kg/m}^2 - \text{hr} \text{ (37 lb/ft}^2 - \text{hr)} \end{aligned}$$

GRATE AREA (A_G)

$$A_G = \frac{\text{firing rate}}{\text{grate loading}} \quad (7.12)$$

$$\begin{aligned} A_G &= R_c / L_G \\ &= 11.15 \text{ m}^2 \text{ (120 ft}^2\text{)} \end{aligned}$$

ARCH HEIGHT H_A CALCULATIONS

Arch height and grate area are related by the following empirical relation in which British units should be used [10].

$$\text{Arch height } H_A = (4/3) * (A_G)^{4/11} \quad (7.13)$$

$$\begin{aligned} H_A &= 4/3(120)^{4/11} \\ &= 8 \text{ ft} = 2.45 \text{ m} \end{aligned}$$

From the construction details of chamber design, arch height and other vertical dimensions are averages based on construction with 60° sprung arches [10].

Ratios of grate length (L) to grate width (W), for various waste feeding rates are given below.

FIRING RATE, lb/hr	L:W
Up to 500 lb/hr	2.0:1 to 2.5:1
> 500 to 750	1.75:1
> 750 to 2000	1.7:1
$R_C > 2000$	1.2:1

Square grates are also acceptable when the length of the incinerator exceeds 3.65 m (12 ft) [10]. In this design problem L:W is selected as 1.2:1;

GRATE LENGTH (L) AND WIDTH (W) CALCULATIONS

$$\text{Grate area } A_G = L * W$$

The standard design consists of 2 to 3 grates in an incinerator. The grate length is calculated as follows: The first grate at the inlet of the feed is used for drying the waste. From the last grate, ash is removed. In order to account for these 10 to 15 percent extra area above that theoretically calculated is provided. Considering 15% extra area:

$$\begin{aligned} \text{Total area of grates} &= 1.15 * 11.15 \\ A_G &= 12.8 \text{ } m^2 \text{ (138 } ft^2) \\ A_G &= \eta * L * W \end{aligned}$$

From Table 1.19a, p1.26, Perry [11],

For central angle 120° :

Height/radius	$= 0.5;$
Chord/radius	$= 1.73205;$
Height/chord	$= 0.288;$
Height	$= chord * 0.288$
	$= 2.74 * 0.288$
	$= 0.8 \text{ m (2.6 ft)}$
Chord/radius	$= 1.732$
Radius	$= 9 * 0.3048 / 1.732$
	$= 1.6 \text{ m (5.2 ft)}$
s	$= \frac{(2*1.6+2.75)}{2}$
	$= 2.975 \text{ m}$
Area of AOB	$= \sqrt{s(s-a)(s-b)(s-c)}$
$A_{AOB} + 1.124 \text{ m}^2$	
(Area of the circular segment)	$= \frac{120}{360} * \pi * 1.6^2$
	$= 2.68 \text{ m}^2$
Area of shaded portion	$= 2.68 - 1.124$
	$= 1.47 \text{ m}^2$
Average height of shaded area	$= 1.47 \text{ m}^2 / 2.75 \text{ m}$
	$= 0.53 \text{ m}$
Average height of chamber	$= 2.45 \text{ m}$
Rectangular section height	$= 2.45 - 0.53$
	$= 1.92 \text{ m}$
Length of the grate	$= 2.77 \text{ m}$
Width of the grate	$= 2.3 \text{ m}$
Number of grates	$= 2$
Average height of the arch from the upper surface of the grate	$= 2.45 \text{ m}$

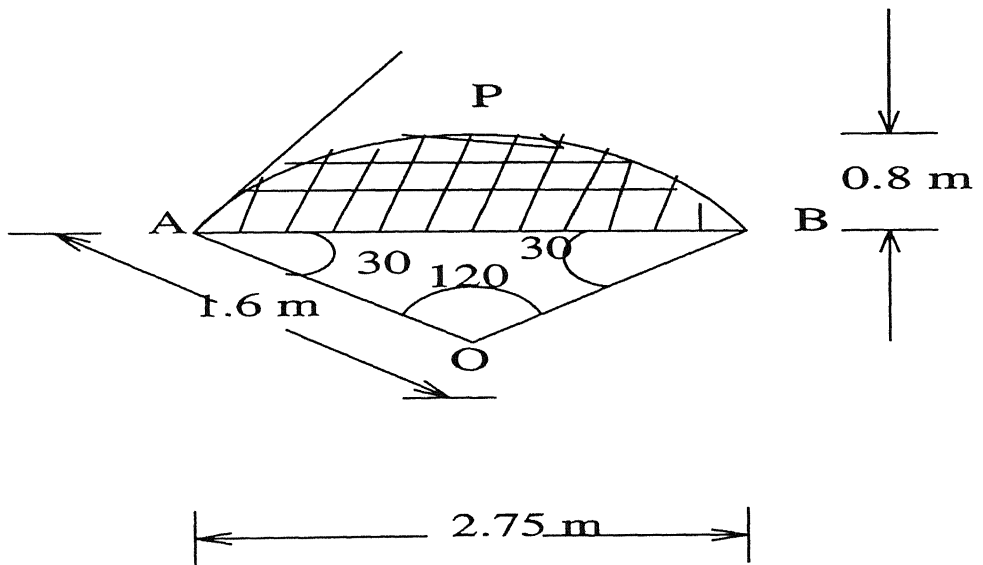
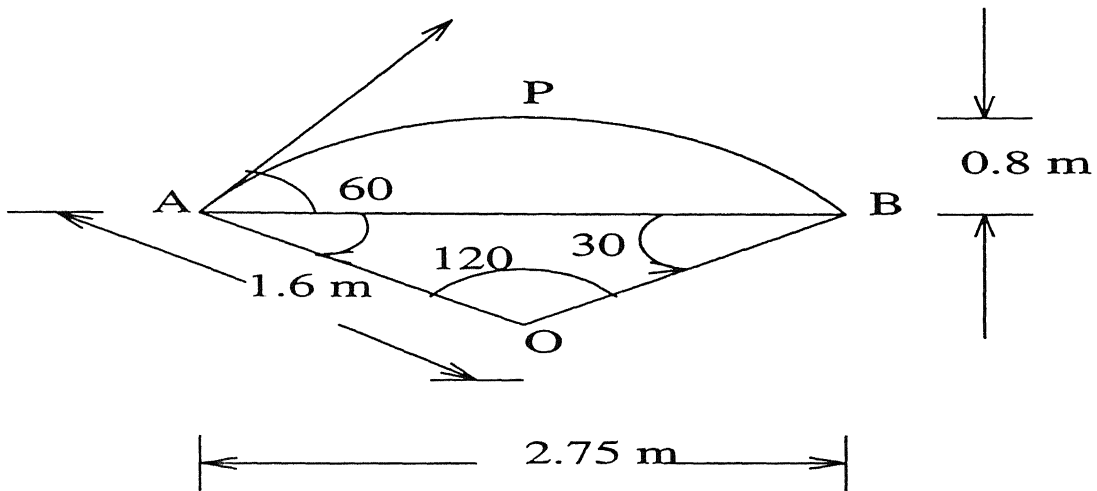
Rectangular box portion ends at a height of 1.92 m from the upper surface of the grate, arch is sprung at an angle of 60° arch height from the top of the rectangular section is 0.88 m , maximum height of the arch from the upper surface of the grate is 2.72 m .

Distribution of air and fuel between primary and secondary chamber:

Air distribution:

Approximately 80% of the total air is fed to the primary chamber. Remaining 20% is fed to the secondary chamber.

Fuel distribution:



From the total quantity of fuel 60 to 70% is sent to the primary chamber and remaining 30 to 40% is sent to the secondary chamber.

$$\begin{aligned}\text{Total air required for the process} &= 23,760 \text{ kg/hr} \\ 80\% \text{ of the total air passed through the primary chamber} &= 19,000 \text{ kg/hr} \\ \text{Volume of air entering primary chamber} &= 16,100 \text{ m}^3/\text{hr}\end{aligned}$$

This amount of air has to be distributed in four burners in the ratio of 20,30,30, & 20.

At the inlet of the waste and at the exit of the ash, air required is less because of the nature of intensive burning. Thus, 20% of air passed through the burners nearby these points.

3. Numbering the burners 1 to 4 from the entrance of the waste to the ash exit, nozzle velocities are calculated.

$$\begin{aligned}\text{Capacity of burners 1 \& 4} &= 3,220 \text{ m}^3/\text{hr} \\ \text{Capacity of burners 2 \& 3} &= 4,830 \text{ m}^3/\text{hr} \\ \text{Residence time in the primary chamber} &= 2 \text{ s} \\ \text{Maximum quantity of air exiting the primary chamber} &= 18,890 \text{ kg/hr} \\ \text{Volume of gaseous products} &= \frac{\text{mass of gases leaving the system}}{\text{density of gaseous mixture at } 900^\circ\text{C}} \\ \text{Volume of primary chamber} &= \text{vol.flow rate} * \text{residence time} \\ &= 61,645 * 2/3,600 \\ &= 35 \text{ m}^3 \\ \text{Volume of primary chamber} &= l * b * h_{avg}\end{aligned}$$

From the above calculations length is 6.21 m

7.13.5 SECONDARY CHAMBER DESIGN

Temperature in the secondary chamber	$= 1,000^{\circ}C$
Residence time	$= 1.5 \text{ s}$
Mass of gaseous products exiting this chamber	$= 25,165 \text{ kg/hr.}$
Volume of gaseous products	$= 92,200 \text{ m}^3/\text{hr}$
Volume of secondary chamber	$= \frac{92,200 \times 1.5}{3,600}$
Gas velocity in the secondary chamber ranges from 1.5 to 3 m/s [1].	
Considering linear velocity of gases as 3 m/s;	
The length of the chamber	$= 4.5 \text{ m}$
The secondary chamber is a cylindrical one;	
$\pi r^2 l$	$= 38.4 \text{ m}^3$
r	$= \sqrt{\frac{38.4}{\pi \times 4.5}}$
	$= 1.6 \text{ m}$
where r is radius of the chamber	
l is length of the chamber	
Three air nozzles are used in the secondary chamber.	
Capacity of each nozzle	$= 1,585 \text{ kg/hr.}$
Fuel to the primary chamber @ 70%	$= 118 \text{ kg/hr.}$
Fuel to the secondary chamber @ 30%	$= 50 \text{ kg/hr}$

Ash removal system is not required in the secondary chamber. However an access door is provided to clean the secondary furnace frequently. Figure 7.4 and Figure 7.5 show a primary and secondary combustion chambers respectively.

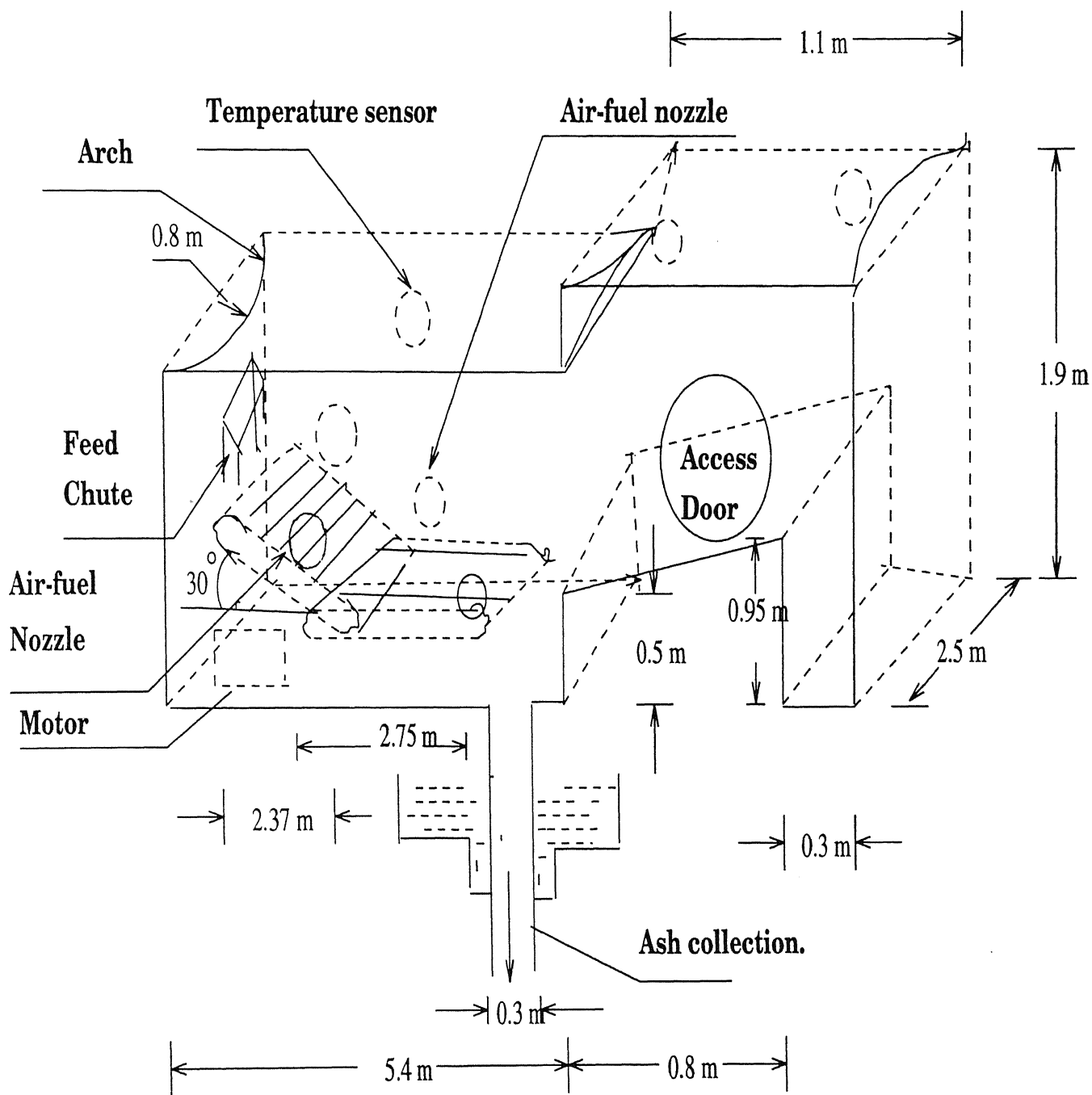


Figure 7.4: Primary combustion chamber

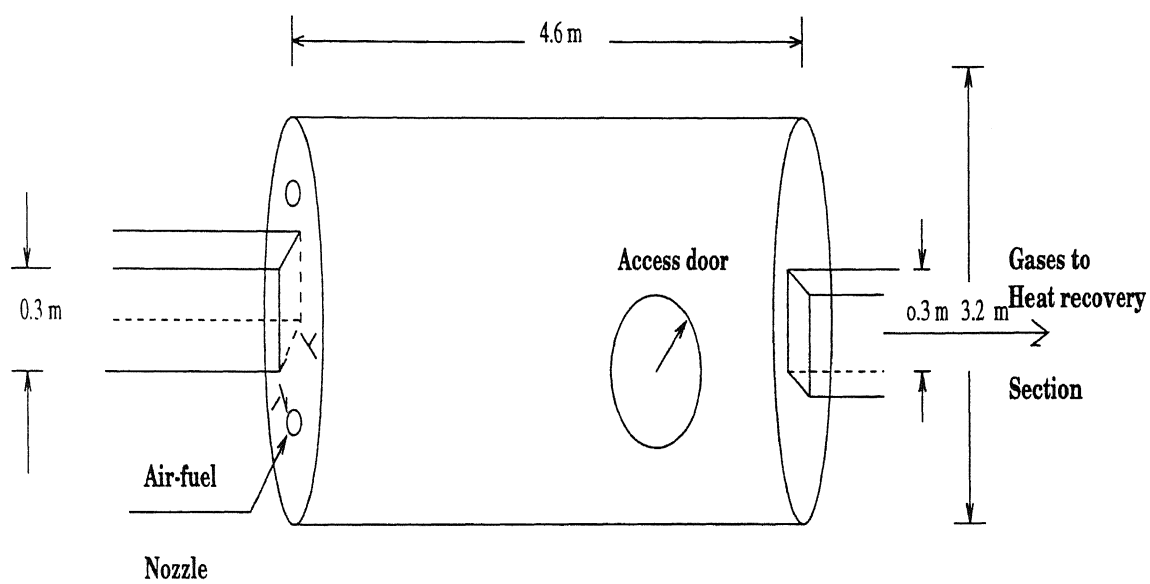


Figure 7.5: Secondary combustion chamber

7.14 DESIGN B: DESIGN OF MULTIPLE HEARTH INCINERATOR

7.14.1 WASTE CHARACTERISTICS

The waste characteristics are based on the Executive summary [6] and General Electric company's solid waste technology assessment [25].

CPCB Waste Category no: 15

Ultimate Analysis of wastes from Pesticides Manufacturing

Water content	= 55%;
Non-combustible, non-volatile and ash	= 5%;
Carbon	= 25%;
Hydrogen	= 3%;
Sulfur	= 3%;
Nitrogen	= 5% ;
Chlorine	= 1%;
Oxygen	= 3%;
Total	= 100%
Mass flow rate of waste	= 2,000 <i>kg/hr</i> ;
Net heating value of waste	= 1,1180 <i>kJ/kg</i> (4805 <i>Btu/lb</i>);
Temperature of destruction	= 1000°C
Residence time in the multiple hearth furnace	= 2 <i>s</i> ;
Residence time in the after burner system	= 1.5 <i>s</i> ;
Excess air percent	= 60;
Fuel oil characteristics:	
Gross heating value of fuel oil	= 45,125 <i>kJ/kg</i> (19,400 <i>Btu/lb</i>)
Net heating value of fuel oil at 1000°C	= 20,380 <i>kJ/kg</i> @ 30% excess a
Density of fuel oil	= 864 <i>kg/m³</i> ;
Elemental composition:	
Carbon	= 87.5%;
Hydrogen	= 12.5%
Excess air used for fuel oil burning	= 30%;

7.14.2 MATERIAL BALANCE

Feed rate of the waste	= 2,000 <i>kg/hr</i>
Moisture content of the waste	= 1,100 <i>kg</i>
Dry feed	= 900 <i>kg</i>
Non-combustibles	= 100 <i>kg/hr</i>
Combustible material content	= 800 <i>kg</i>
Total heat content of the waste	= 22.36×10^6 <i>kJ/kg</i>
Theoretical oxygen required	= 1,875 <i>kg</i>
Actual air requirement @ 60% excess air:	
Oxygen required	= 3,000 <i>kg/hr of operation;</i>
Nitrogen present in the air 9,875 <i>kg</i> ;	
Total air	= 12,875 <i>kg</i> ;
Total moisture:	
Water in the waste	= 1,100 <i>kg</i>
Water produced due to burning of combustibles	= 540 <i>kg</i>
Moisture from air (Please refer design A.)	= 129 <i>kg</i>
Total moisture in the combustion products	= 1,769 <i>kg</i>
Total mass into the furnace	= 15,004 <i>kg/hr</i>

COMBUSTION ANALYSIS

In the combustion process *HCl* produced would reduce water generation, however, the quantity is very less and hence this effect is neglected in these calculation.

<i>CO</i> ₂ produced	= 1,835 <i>kg</i> ;
<i>SO</i> ₂ produced	= 120 <i>kg</i> ;
<i>HCl</i> produced	= 20 <i>kg</i>
Steam at the outlet of the furnace	= 1,769 <i>kg</i> ;
Unreacted oxygen	= 1,185 <i>kg</i> ;
Nitrogen leaving	= 9,975 <i>kg</i> ;
Total mass leaving the furnace	= 15,004 <i>kg/hr</i>

7.14.3 FURNACE TEMPERATURE CALCULATIONS

Furnace temperature is calculated by the following relation [10].

$$\begin{aligned}
 T - t &= \frac{\text{heat input} * \text{correction factor}}{W_g * S_{pm}} \\
 &= \frac{4805 * 4405 * 0.675}{0.675 * 33011 \text{ kg of combustibles}} \\
 &= 1545^\circ C \\
 T &= 1620^\circ F \\
 &= 880^\circ C
 \end{aligned}$$

Here calculations are made on the basis of the assumption that air enters from atmosphere.

7.14.4 HEAT BALANCE

Combustion products exit the secondary chamber at a temperature of $1000^\circ C$

$$\begin{aligned}
 \text{Enthalpy of air @ } 1000^\circ C &= 1,060 \text{ kJ/kg} \\
 \text{Enthalpy of steam @ } 1000^\circ C \text{ and 1 atm} &= 4,575 \text{ kJ/kg}
 \end{aligned}$$

HEAT LOSS BY ASH

The ash temperature leaving the incinerator is assumed to be $500^\circ C$.

$$\begin{aligned}
 \text{Mean heat capacity of ash} &= 0.711 \frac{\text{kJ}}{\text{kg} \cdot K} \\
 \text{Ash heat content} &= \text{mass flow rate of ash} * \\
 &\quad \text{heat capacity of ash} * \text{temperature difference} \\
 &= 100 * 0.711 * 475 \\
 &= 33,770 \frac{\text{kJ}}{\text{hour of operation}}
 \end{aligned}$$

RADIATION LOSSES FROM THE FURNACE

As a good approximation, the expected loss from radiation can be taken as 2.5 percent of the heat input [5]. (Please refer radiation loss section of design A.)

7.14.5 CALCULATION OF HEAT DEFICIENCY

Similar to heat deficiency calculation of design A;

Using C_p values and mass flow rates of respective components,

Total heat required for
complete combustion

$$\begin{aligned}
 &= \sum m_i C_{p_i} \Delta T + \text{enthalpy of moisture} \\
 &= (1835 * 0.3 + 1185 * 0.275 + 9975 * 0.295 + 120 * 0.205 + 21 * 0.22 \\
 &\quad * 4.187 * 975 + 1769 * 4575) \\
 &= 23.83 * 10^6 \text{ kJ/hr}
 \end{aligned}$$

Accounting for radiation losses and rabble arm and shaft heating losses, considering a heat loss percentage of 2.75 of the total, the total heat required to raise the temperature of the gases to the desired temperature (i.e., 1000°C) can be calculated.

Heat required

$$= 24.5 * 10^6 \frac{\text{kJ}}{\text{hr of operation}}$$

Total heat available from the combustion of waste

$$\begin{aligned}
 &= (2,000 \text{ kg/hr}) * (11,180 \text{ kJ/kg}) \\
 &= 22.36 * 10^6 \frac{\text{kJ}}{\text{hr. of operation}}
 \end{aligned}$$

Heat deficiency

$$\begin{aligned}
 &= (\text{heat required} - \text{heat available}) \\
 &= (24.5 * 10^6 - 22.36 * 10^6) \frac{\text{kJ}}{\text{hr of operation}} \\
 &= 2.14 * 10^6 \frac{\text{kJ}}{\text{hr. of operation}}
 \end{aligned}$$

7.14.6 FUEL REQUIREMENT CALCULATIONS

Air required for fuel oil	$= 16.16 \frac{\text{kg}}{\text{liter of fuel oil}}$
Dry gas generated	$= 16.01 \frac{\text{kg}}{\text{liter of fuel oil}}$
Water generated	$= 1.05 \frac{\text{kg}}{\text{liter of fuel oil}}$
Fuel oil required	$= \frac{\text{heat deficiency}}{\text{net heating value of fuel oil}}$ $= \frac{2.14 \times 10^6 (\frac{\text{kJ}}{\text{hr. of operation}})}{20380 (\frac{\text{kJ}}{\text{kg. of fuel}})}$ $= 105 \text{ kg/hr. of operation}$ $(122 \text{ liters/hr. of operation})$
Air flow for the combustion of fuel @ 30 excess air	$= \text{air required per liter of fuel oil} \times$ $\text{vol. flow rate fuel oil in liters.}$ $= 16.16 \times 122$ $= 1970 \frac{\text{kg of air}}{\text{hr. of operation}}$
Moisture accompanying air	$= 20 \text{ kg/hr } (@ 50\% \text{ relative humidity and } 25^\circ\text{C})$
Combustion products generated	$= 16.01 \times 122$ $= 1953 \frac{\text{kg}}{\text{hr. of operation}}$
Moisture generated from fuel oil combustion	$= 1.05 \times 122$ $= 128 \text{ kg/hr}$
Heat in the gas at the outlet of the chamber	$= \text{heat from combustion of waste}$ $+ \text{heat from combustion of fuel}$ $= ((22.5 + 4.74) \times 10^6) \times 0.9725 \frac{\text{kJ}}{\text{hr. of operation}}$ $- \text{ash heat content}$ $= 26.46 \times 10^6 \frac{\text{kJ}}{\text{hr. of operation}}$
Total combustion products exiting the secondary chamber	$= 15,090 \text{ kg/hr}$
Total moisture exiting the secondary chamber	$= 1,917 \text{ kg/hr}$
Ash exiting the chamber	$= 100 \text{ kg/hr.}$

7.14.7 SIZING UP OF MULTIPLE HEARTH FURNACE

In a typical multiple hearth furnace the first two upper hearths comprise of the drying zone, where the sludge cake gives up moisture while cooling the hot flue gases. In the bottom hearth the air enters the chamber and cools the ash and subsequently the ash is removed from the system. Approximately 50 kg of moisture is released per square meter of hearth area per hour of operation. When the moisture content within the furnace is reduced to nearly 30%, the sludge begins to burn. The burning rate is approximately 50 kg

per square meter of hearth area per hour. The furnace heat release rate is approximately $3.75 * 10^5 \frac{kJ}{m^2-hr}$, applied above the hearths [1, 5].

Brunner [5] has developed a set of multiple hearth furnace sizing curves from the above criteria. Furnace sizing is dependent on the moisture content and quantity of waste to be incinerated.

In the present design problem, moisture content is 55% and the quantity of waste is 2 tons per hour. From the multiple hearth furnace sizing curves available [5], the following are obtained.

Diameter of the hearth = 1.85 m (6 ft)

Number of hearths = 7

To spread the waste on the hearth and push the waste to the next hearth, a vertical shaft is positioned in the center of the furnace. The central shaft rotates and drives the rabble arms. (Rabble arms are attached to the shaft above each hearth.) A knocker blade like arrangement or a series of rabble teeth on each rabble arm wipes sludge across each hearth.

Solids residence time in the furnace is around 4 to 5 minutes whereas the gas residence time is only two seconds. To give sufficient residence time for solids the shaft is rotated very slowly. Typically it is of the order of 3/4 to 2 revolutions per minute. In the present design problem, solids residence time is taken as 5 minutes and the shaft is driven at a speed of approximately 1.4 revolutions per minute.

SHAFT RABBLE ARM AND TEETH

To reduce power consumption, the mass of the shaft, rabble arm and teeth should be reduced. The incineration temperature is $1,000^{\circ}C$ and it may be $1,200^{\circ}C$ or more in some other cases. The shaft and its accessories should withstand that high temperature. In order to meet both the above problems, hollow shaft, rabble arm and teeth are designed. Through the hollow shaft cooling air is sent. It maintains the temperature of the shaft

constant (reduces overheating of the shaft, rabble arm, etc.). This cooling air which is preheated at the outlet of the furnace can again be sent into the furnace as preheated combustion air. Or it can be sent to the secondary combustion chamber [1, 5].

Of the total air, 80% is sent to the primary chamber and remaining to the secondary chamber. Of the total fuel 70% is sent to the primary furnace and remaining to the secondary furnace.

Fuel oil burners: in the hearth furnace, four fuel oil burners are arranged, one for each hearth starting from second hearth to the sixth hearth.

Mass flow of air into the primary furnace	= $0.8 * 14865 \text{ kg/hr}$
	= $11,900 \text{ kg/hr}$
Vol. flow rate of air from blower at room temperature	= $\frac{11,900}{\frac{1.28}{0.082 * 296}}$
	= $10,385 \text{ m}^3/\text{hr} \text{ (} 2.9 \text{ m}^3/\text{s)}$
Shaft diameter	= 0.3 m/s
Rabble arm length	= 1.4 m
Width of rabble arm	= 0.3 m
Number of teeth	= 5 per rabble arm (i.e., 10 per hearth)

VOLUME OF PRIMARY CHAMBER

This can be calculated from the volume of the gases handled in the system.

Maximum volume of the combustion products in the hearth furnace	= $\frac{\text{Mass of gaseous products}}{\text{Density of gaseous mixture}}$
	= $\frac{14,070}{\frac{1.29}{0.082 * 11,73}}$
	= $46,675 \text{ m}^3/\text{hr}$
Volume of the hearth furnace	= $\frac{46,675 \text{ m}^3/\text{hr} * 2 \text{ s}}{3,600 \text{ s/hr.}}$
	= 26 m^3
Diameter of the furnace	= 1.85 m
Height of the furnace	= 9 m (excluding hearth thickness)
Hearth thickness (approximately)	= 0.3 m
Spacing between two hearths	= 1 m

A multiple hearth furnace with design specifications is shown in Figure 7.6. Neglecting

the volume of the shaft, rabble arms and teeth the following design specifications could be made.

DESIGN SPECIFICATIONS

Number of hearths	= 7
Diameter of the hearth	= 1.85 <i>m</i>
Volume of the furnace	= 26 <i>m</i> ³
Spacing between two hearths	= 1 <i>m</i>
Number of rabble arms per hearth	= 2
Number of teeth per rabble arm	= 5
Length of rabble arm	= 1.4 <i>m</i>
Width of rabble arm	= 0.3 <i>m</i>

SECONDARY COMBUSTION CHAMBER

Design of secondary combustion chamber is similar to the design A.

(Please refer secondary chamber design of design A.)

Temperature in the secondary chamber	= 1,000 ⁰
Residence time in the secondary chamber	= 1.5 <i>s</i>
Volumetric flow rate in the secondary chamber	= 54,715 <i>m</i> ³ / <i>hr</i>
Length of the secondary chamber	= 4.5 <i>m</i>
Diameter of the secondary chamber	= 2.5 <i>m</i>

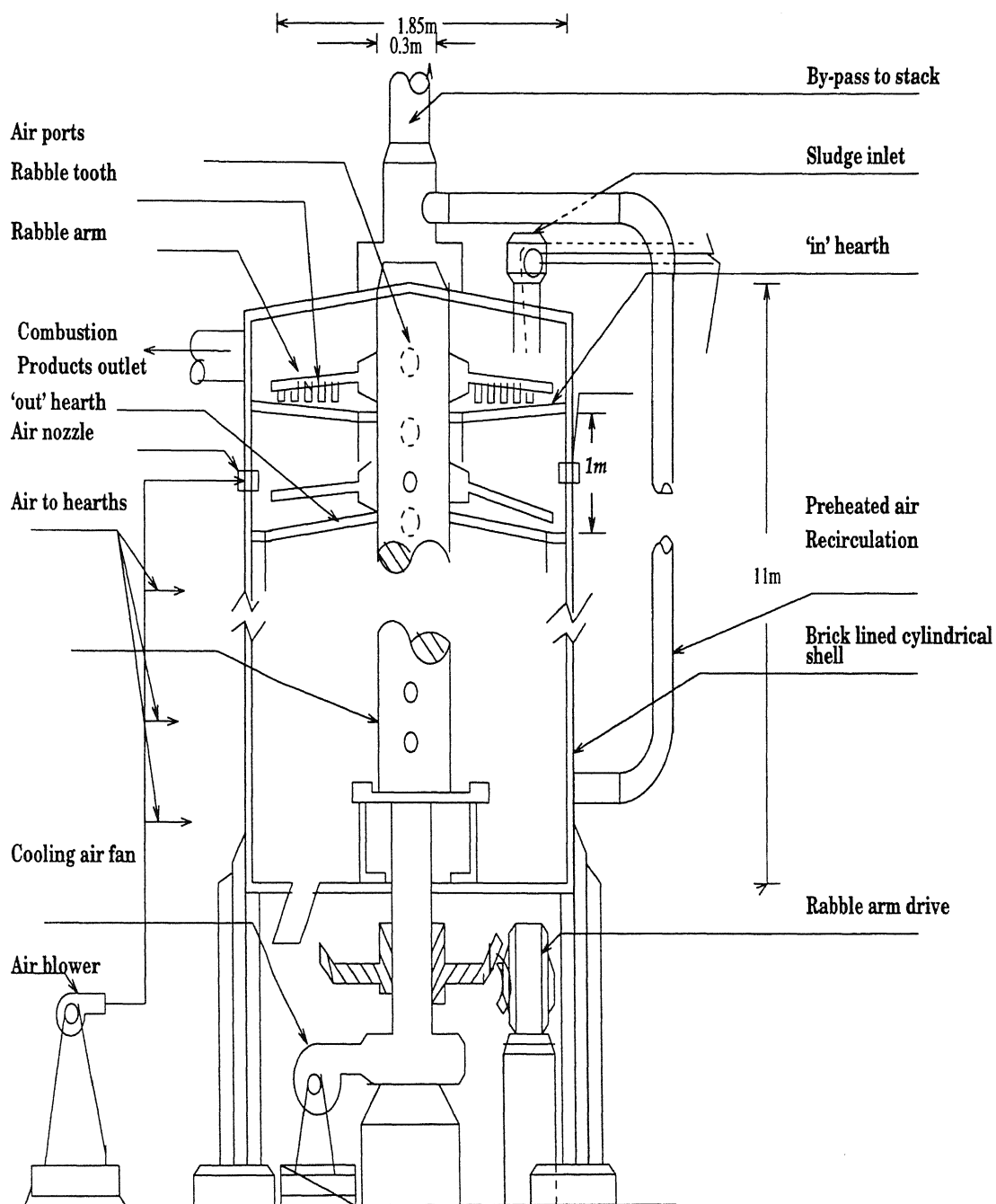


Figure 7.6: Multiple hearth furnace

Chapter 8

WASTE HEAT RECOVERY

a boy playing on sea shore
... now and then finding a smoother pebble
... whilst the great ocean of truth lay all undiscovered before me.

Sir Isaac Newton.

Combining heat recovery and utilization with incineration in a well designed and operated continuous feed plant may be justified, especially when the heating value of the waste is high. In this chapter advantages of heat recovery have been listed. Possibilities of heat recovery for the design problem A of the previous chapter are also explored.

8.1 ADVANTAGES OF ENERGY RECOVERY IN INCINERATION PLANTS

Many of the following possible uses for the heat developed by incineration of refuse have been proved by operating installations in the United States, Japan and Europe [5].

1. Power generation for plant use comprising high pressure boilers and electricity generating equipment.
2. Steam and/or power generation for the use to nearby users, such as market, or to the electricity board.

3. Waste purification or desalination through evaporators and for other processes.
4. High temperature, high pressure water generation for heating adjacent complexes, cooling by reversible steam cycles with low or medium pressure steam is also possible.
5. Gas turbine power generation with closed systems.
6. As a source for preheating the waste/combustion air, which will enhance combustion efficiency. By this method the quantity of supplemental fuel required can be reduced (i.e., reduction in operating costs).

The inclusion of heat recovery system in an incinerator system must be evaluated to justify its cost.

8.1.1 AIR PREHEATING WITH WASTE ENERGY

By preheating the combustion air to be fed into the incinerator, the combustion efficiency can be enhanced. The combustion products from the secondary chamber is sent to the

continued

heat recovery section. This preheating equipment is a gas-to-air heat exchanger. Hot combustion gases are passed through the tubes of the heat exchanger while combustion air is directed through the shell of the heat exchanger.

8.3 WATERWALLS

Water walls in the furnace have many advantages as well as certain limitations, which must be thoroughly understood if the desired results are to be obtained without excessive maintenance [10]. The advantages include:

1. Reduction in refractory maintenance by elimination of exposed furnace walls and arches.
2. The ability to operate with high flame temperature without excessive slag formation.
3. Effective energy utilization.

The disadvantages include:

1. In the incinerator highly corrosive gases are produced and the temperature is also very high, hence, cost of corrosion prevention, materials, etc., are very high.
2. Added maintenance costs, operational problems, etc.

8.3.1 APPROACH TEMPERATURE (T_x)

Approach temperature is the difference between the exit gas temperature from the heat recovery system and the steam temperature. For perfect systems $T_x = 0$ but this requires infinite area. For real systems, approach temperature normally ranges from 15 to 100°C. If the approach temperature is known, available heat can be easily calculated [5]. Let the available heat be Q ;

$$Q = WH_T - H_{T_{EF}} \quad (8.1)$$

where

W = gas flow rate;

T_F = temperature of the hot flue gas;

T_{EF} = temperature of the flue gas exiting heat recovery system;

H_{TF} = enthalpy of gas stream at T_F ; and

H_{TEF} = enthalpy of gas stream at T_{EF} .

If the approach temperature is assumed depending on the desired steam pressure and temperature, available heat can be calculated. A sample calculation of available heat for the design A of the seventh chapter is shown here. From energy and material balances of design A (Chapter 7)

Total combustion gas exiting secondary chamber	=23,605 kg/hr
Total moisture exiting the secondary chamber	=2,010 kg/hr
Heat in the outlet gas stream	=37.17 * 10 ⁶ kJ/hr
Temperature of the outlet gases	=1,000°C

Available heat and percentage heat recovery calculations are shown in Figure 8.1. In these calculations the approach temperature (T_x) is assumed as 50°C. Similar calculations can be made for different approach temperatures.

It is very important to note that the purpose of the incinerator is not to recover waste heat but to destroy the hazardous constituents present in it. If considerable amount of heat can be economically recovered from the incinerator, without affecting the system performance, this should be incorporated in the design [5]. This helps in reducing the overall cost of operation and is a welcome point.

Steam pressure, kPa	Steam temperature, °C	Recovery unit exit gas temperature, °C	Enthalpy of moisture kJ/kg	Enthalpy of combustion products, kJ/kg	Total enthalpy of moisture GJ/hr	Total enthalpy of combustion gases, GJ/hr	Total heat exiting recovery section, GJ/hr	Available heat, GJ/hr	percent heat recovery
245	127	177	2,808	184	5.65	4.34	10	27.17	73.1
932	177	227	2,875	219	5.78	5.16	10.94	26.23	70.6j
2,640	227	277	2,975	210	5.98	6.37	12.35	24.82	66.7
6,119	277	327	3,075	321	6.18	7.57	13.75	23.42	63

Figure 8.1: Percent heat recovery calculations

Chapter 9

AIR POLLUTION MONITORING AND CONTROL

Pollution controls do not solve problems.

They only alter the problem, shifting it from one form to another.

Minnesota Mining and Manufacturing Company

Incineration produces combustion products. These combustion products contain large quantities of sulfur oxides, carbon oxides, nitrogen oxides and others. Apart from these highly hazardous chemicals like dioxins, poly chlorinated biphenyls (PCBs), etc., are also produced in the incinerator. Highly turbulent conditions in the incinerator makes ash and other particles carry over with the gaseous stream. Hence it becomes very important to purify the gases before releasing them into the atmosphere. In this chapter particulate removal by cyclone separator, sulfur oxides and hydrogen chloride removal, etc., are given. Stack design is also presented. It is very necessary to know the type and the amount of hazardous gases produced, their efficiency of removal, and their concentrations in the gaseous stream, which is finally released to the atmosphere.

9.1 DUST AND FLY ASH COLLECTION

Highly turbulent combustion conditions inside the incineration chambers, high velocity of gases, etc., result in carry over of particles, non-combustibles, fly ash, etc., in the gaseous stream. For the following reasons, dust has to be removed from the gaseous stream, before releasing it into the atmosphere and the absorber section.

1. Air pollution control, to meet regulatory measures.
2. Equipment maintenance reduction.
3. Safety or health hazard elimination.

Two types of dust collection equipment: cyclone separator and electrostatic precipitator, are described in detail here.

9.1.1 CYCLONE SEPARATOR

The most widely used type of dust collection equipment is the cyclone separator, in which dust laden gas enters a cylindrical or conical chamber tangentially at one or more points and leaves through a central opening. The dust particles, by virtue of their inertia, will tend to move outside toward the outside separator wall from which they are led into the receiver. At the operating conditions commonly employed, the centrifugal separating force or acceleration may range from five times gravity in very large diameter, low-resistance cyclones to 250 times gravity in very small high resistance units. The immediate entrance to a cyclone is usually rectangular [26].

Of the different cyclone types, the reverse flow cyclone is the most commonly used. It has tangential inlet with axial gas and dust discharge. Standard cyclone design configurations are given in Table 9.1 [27]. All dimensions are ratios with respect to 'D'.

Term	Description	Stairmaid recommendations	Swift recommendations
D	Body diameter	1.0	1.0
a	Inlet height	0.5	0.44
b	Inlet width	0.2	0.21
s	Outlet length	0.5	0.4
De	Outlet diameter	0.5	0.4
h	Cylindrical shaft	1.5	1.4
H	Overall height	4.0	3.9
B	Dust outlet diameter	0.375	0.4

Table 9.1: High efficiency cyclone design specification [27].

GAS FLOW PATTERNS

TANGENTIAL GAS VELOCITY

Gas entering the cyclone forms a confined vortex in which the tangential velocity, v_t , is related to the distance from the cyclone axis, r , by

$$v_t r^n = k \quad (9.1)$$

where n is called vortex exponent (dimensionless) and it varies from 0.5 to 0.8.

RADIAL VELOCITY

As gas spirals down the outside of the cyclone, it is continuously drawn off into the vortex core. Radial velocities just below the gas outlet is approximately 10 times higher than the radial velocities near the dust outlet.

AXIAL VELOCITY

Gases within the cyclone flows down along the walls, conveying collected dust to dust outlet. Near the cyclone axis the flow is upward.

PRESSURE DROP

The pressure drop through a cyclone as well as the friction loss is most conveniently

expressed in terms of velocity head based on the immediate cyclone inlet area. Miller and Lissman [11], proposed an empirical relation for pressure drop, which is as follows:

$$\Delta P_{cv} = k \left(\frac{D_c}{D_e} \right)^2 \quad (9.2)$$

where k is a constant whose value is 3.2, for the following range in proportions. $B_c/D_c = 1/8$ to $3/8$; $H_c/D_c = 1.0$; $D_e/D_c = 1/4$ to $3/4$.

where B_c = breadth of the cyclone inlet

D_c = diameter of the cyclone

D_e = diameter of the gas outlet

H_c = height of the cylindrical cyclone portion

For smaller values of D_e/D_c , value of k increases.

SALTATION VELOCITY

The saltation effect places an upper limit upon the flow rate or inlet velocity, which may be used in the case of solids. This is due to re-entrainment or the lack of deposition of particles which occurs at high velocities, and is analogous to the pick up of solids at high bulk flow in horizontal pipe lines. Klen and Zenz [27], have established a relationship for the optimum inlet velocity and the velocity at which reentrainment becomes significant. The saltation velocity (U_s) is given empirically as follows:

$$U_s = 2.055 D^{0.067} U_T^{2/3} (4g\rho_p\mu)(3\rho_f^2) \frac{(b/D)^{0.4}}{(1 - b/D)^{1/3}} \quad (9.3)$$

in which units of feet, pound, and seconds must be used,

where ρ_f = density of fluid;

ρ_p = density of particles;

μ = viscosity of fluid; and

p = pressure.

Kalen and Zenz [27], state that the maximum collection efficiency occurs at $U_T/U_s \cong 1.25$, and significant reentrainment occurs at $U_T/U_s \cong 1.36$. where U_T is tangential velocity.

ity. For $U_T/U_S \cong 1.25$; the above equation becomes

$$U_T = \frac{16.95 * D^{0.201} (b/D)^{1.2} (4g\rho_p\mu)}{(3\rho_f^2(1 - b/D))} \quad (9.4)$$

Replacing U_T by Q/ab and rearranging, an equation for D is obtained, which may be used to select a cyclone size for particular configuration, gas flow, particle and gas properties, where Q is volumetric flow rate of gases.

$$D = \frac{0.052Q(1 - b/D)\rho_f^2}{(a/D)(b/D)^{2.2}\mu\rho_p} \quad (9.5)$$

Equation for saltation velocity U_S , does not account for the fact that U_S depends upon particle size. Constant 2.055 in the expression can be replaced by an empirical variable factor F defined as,

$$F = G_a^{0.107} \quad (9.6)$$

for $G_a \geq 1,000$

$F = 4.406/G_a^{0.107}$; otherwise.

where G_a is Galileo number.

$$G_a = \frac{(4g/3)(\rho_p\rho_f d_p^3)}{\mu^2} \quad (9.7)$$

for ρ_f values very small when compared to ρ_p values. Where d_p is diameter of the particles, ρ_p and ρ_f are densities of fluid and particles respectively.

A cyclone separator is designed for design A and shown in Fig.9.1. For this design problem, values suggested by Swift [27] are considered. In the design of cyclone separators, the working conditions to be met are to be clearly specified. They are:

1. Composition, temperature, and pressure of the gases.
2. Size distribution, grain loading, and nature of particulate matter.

3. Rate of flow of gas steam.
4. Desired collection performance, specified in terms of maximum allowable rate or of minimum desirable collection rate of particulates.

Gas flow rate at the exit of the heat recovery system	= 25,615 kg/hr (56,420 lb/hr)
Temperature of exit stream	= 250°C
$\rho_{gas} = \rho_{air} = \rho_f$	= 0.676 kg/m ³ (0.042 lb/ft ³)
Vol.flow rate of gases	= 10.52 m ³ /hr

Density of particles is taken as an approximate ash/cement particles, a typical cyclone separator system encounters. Viscosity of gaseous stream is assumed to be that of air at the operation temperatures.

Density of particles	= 1,500 kg/m ³ (94 lb/ft ³)
Viscosity at 250°C	= $2.75 * 10^{-4}$ g/cm - s ($1.815 * 10^{-5}$ lb/ft - s)
Diameter of the cyclone separator:	
D	= 1.5 m (4.6 ft)
Terminal velocity	= 56 m/s (185 ft/s)
Pressure drop	= $3.2 * (1/0.5)^2$
	= 12.8 inches of water column
Vortex exponent 'n'	= 0.65

Using Swift's [27] high efficiency cyclone specifications (please refer Table 9.1):

Diameter(D)	= 1.5 m
a	= 0.66 m
b	= 0.315 m
s	= 0.5 m
D_e	= 0.6 m
h	= 2.1 m
H	= 5.85 m
B	= 0.6 m

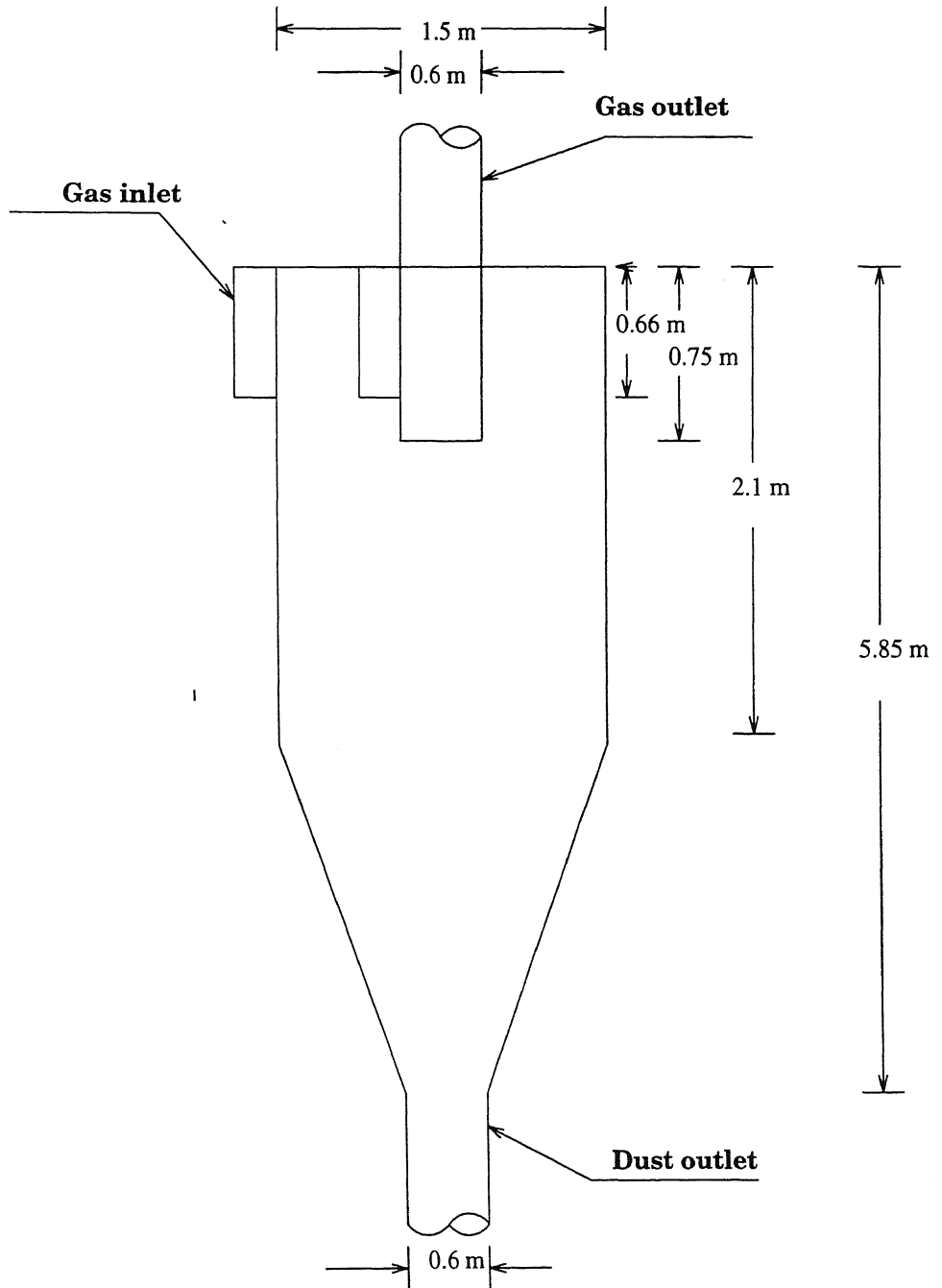


Figure 9.1: Cyclone separator

9.1.2 ELECTROSTATIC PRECIPITATOR

Electrostatic precipitation is a process by which particles are suspended in a gaseous stream are electrically charged and separated from the gas stream under the action of an electric field. There are two electrodes, emitting and collecting electrodes. A sufficiently high voltage to the emitting electrodes is applied to produce corona discharge. Suspended particulate matter is charged by bombardment by gaseous ions and migrates toward the grounded collecting plates due to the electrostatic forces.

Electrostatic precipitators effectively collect fine particles (less than $1\mu\text{m}$ in diameter) but are unable to capture noxious gases [1, 27]. They perform poorly on particles with high electrical resistivity.

ADVANTAGES

1. Efficient removal of fine particles.
2. Low pressure drop and operating costs.

DISADVANTAGES.

1. Relatively high capital cost.
2. Sensitive to changes in flow rate.
3. Particle resistivity affects removal and economics.

When the waste contains toxic metals, which is carried by the flue gases, is significant. Electrostatic precipitators are more efficient in trapping fly ash.

9.2 SULFUR OXIDES AND HYDROGEN CHLORIDE REMOVAL

Large quantities of sulfur oxides and hydrogen chloride, etc., are produced in the incinerator. Their concentrations have to be reduced to within acceptable limits, before releasing

the gases into the atmosphere. There are wide variety of sulfur oxides and hydrogen chloride removal processes available. Some of them are [21, 26, 27]:

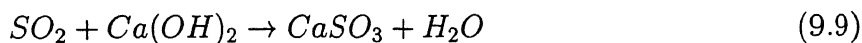
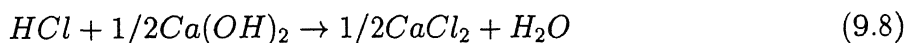
- Absorption in liquids (e.g.: lime /limestone slurry, alkaline fly ash slurry, magnesia, sodium hydroxide, carbonate, or sulfide slurry, NH_3/NH_4OH /ammonium sulfite slurry, etc.).
- Absorption by moist particles (e.g.: in spray driers sodium carbonate or lime is used).
- Sorption by solids (e.g.: by reaction: limestone, metal oxides, alkalised alumina, etc.).
By absorption: carbon and non-reactive adsorbents.
- Gas phase conversion. By oxidation: (e.g.: carbon/reducing gas is used), by reduction, etc.

For the design problem of our interest, most widely used limestone/lime process is selected. the following factors are to be considered in the SO_2 and HCl removal processes.

1. Amount of SO_2 and HCl to be removed per hour of operation.
2. Suitability of the process.
3. Absorber selection.
4. thickened slurry disposal.
5. Efficiency of SO_2 and HCl removal
6. Slurry/absorbent pumping.
7. Local pollution control regulations to be met.

9.2.1 LIME/LIMESTONE PROCESS

Lime/limestone slurry is used to react with the effluent gases in an absorber. This process removes SO_2 and HCl considerably. The reactions involved can be represented as follows:



Basic requirements include:

1. Scrubber for contacting gas with the absorbent slurry.
2. A holding tank for the slurry.
3. A separator to remove spent solids from the liquid absorbent.
4. A system to feed fresh lime/limestone into the circuit.

OTHER ACCESSORIES INCLUDE:

1. Particulate removal device to preclean the feed gas .
2. A mist eliminator following the scrubber.
3. A pre heater to warm the product gas before it is exhausted following the scrubber.
4. Pumps, blowers, and controls.

Key items which must be evaluated in the design of lime /limestone systems include: (1)absorbent selection(lime vs limestone); (2) absorbent cycle design (slurry concentration, recycle rate, etc.); (3) absorber type; (4) mist eliminator; (5)preheater; and (6) materials of construction.

Central Pollution Control Board (CPCB) regulations:

- Combustion efficiency (CE) of the incinerator shall be at least 99.99%. It is computed as follows:

$$CE = (\%CO_2)/(\%CO_2 + \%CO) * 100 \quad (9.10)$$

- The temperature of the primary chamber shall be $900^\circ C$. The secondary combustion chamber gas residence time should be at least one second at $1,000$ to $1,050^\circ C$, with the minimum of 3% oxygen in the stack.
- Particulate matter = $100 mg/Nm^3$
- Sulfur dioxide = $150 mg/Nm^3$
- Nitrogen oxides = $450 mg/Nm^3$
- HCl = $50 mg/Nm^3$
- Minimum stack height should be 30 meters.

These regulations were obtained by personal communication with CPCB.

From design A (Chapter 7)

SO_2 produced	= 200 kg/hr
HCl produced	= 62 kg/hr
Emission standards:	
SO_2	= 150 mg/ Nm^3
HCl	= 50 mg/ Nm^3
Total gaseous products flow from the cyclone	= 25,165 kg/hr
Volumetric flow rate into the absorber	= $\frac{25,615}{\frac{1+29}{0.082 \cdot 273}}$
	= 19,775 Nm^3/hr

SO_2 :

$\frac{200 \cdot 10^6}{19,775} \text{ mg}/Nm^3$ is to be reduced to $150 \text{ mg}/Nm^3$

i.e., $10,115 \text{ mg}/Nm^3$ is to be reduced to $150 \text{ mg}/Nm^3$

Similarly for HCl :

3,135 mg/Nm^3 is to be reduced to 50 mg/Nm^3

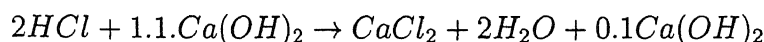
Total SO_2 to be removed = 197 kg/hr .

Total HCl to be removed = 61 kg/hr .

Assuming complete chemical reaction of SO_2 and HCl [21] at 10% and 30% excess, to achieve SO_2 and HCl control, $Ca(OH)_2$ requirement is calculated.

Neutralization reactions:

For HCl :



For SO_2 :



Gas flow rate at the inlet of the absorber = 19,775 Nm^3/hr

Gas flow rate at the exit of the absorber = 19,575 Nm^3/hr

Nearly 99% of the SO_2 and 99% of HCl have to be removed.

HCl to be removed = 1.675 $kmol/hr$

SO_2 to be removed = 3.08 $kmol/hr$

$Ca(OH)_2$ requirement for the system is calculated based on the stoichiometric equations presented above.

1 $kmol$ of SO_2 requires 1.3 $kmol$ of $Ca(OH)_2$

$Ca(OH)_2$ requirement for SO_2 = 4.017 $kmol/hr$

$Ca(OH)_2$ requirement for HCl = 0.92 $kmol$

Mass of $Ca(OH)_2$ required per hour of operation = 366 kg

The spent solids generated include $Ca(Cl)_2$, $Ca(SO)_4$ and are calculated from expressions presented above.

Mass of $Ca(Cl)_2$ produced = $61 \times 111 / 73 = 97$ kg/hr .

Mass of $Ca(SO)_4$ produced = $197 \times 120 / 64 = 370$ kg/hr .

Total mass of solids in the sludge (except $Ca(OH)_2$) = $(370 + 97) = 467$ kg .

The following operating conditions are recommended for SO_2 absorption [27] by lime process.

Solids in slurry	= 12%, by weight
L/G in gal/MCF	= 60
Liquid circulation rate	= $158 \text{ m}^3/\text{hr}$.
Purge rate calculations:	
Total solids produced	= 467 kg/hr

Assuming purge rate is 5% total dissolved solids, purge volumetric flow rate is $9.3 \text{ m}^3/\text{hr}$. This purge slurry can be thickened and the liquid phase can again be utilized in the absorber. Sludge generated can be safely landfilled.

9.3 STACK DESIGN

This whole section is based on Gupta [8]. Treated gas products are disposed into the atmosphere through stack. Dispersion of gaseous pollutants depends on the following:

1. Stack height.
2. Atmospheric stability.
3. Local wind velocity.
4. Temperature of the gases.
5. Velocity of the exit gas stream.
6. Plume rise, etc.

9.3.1 PLUME RISE

For a continuous point release, the ground level concentration is given by the following expression.

$$C(x, y, z) = \frac{Q}{\pi\sigma_y\sigma_z} \exp(-1/2 * (y^2/\sigma_y^2 + z^2/\sigma_z^2)) \quad (9.11)$$

No dispersion is in X direction, which is downwind direction. If the source is elevated (e.g.: chimney), then

$$C(x, y, z) = \frac{Q * \exp(-y^2/2\sigma_y^2)}{2\pi\sigma_y\sigma_z u} \left(\exp\frac{-(z-H)^2}{2\sigma_z^2} + \exp\frac{-(z+H)^2}{2\sigma_z^2} \right) \quad (9.12)$$

where Q= Continuous release rate, kg/s;

H= height of source from ground;

C= concentration of pollutant;

The following dispersion equations are deduced; and

σ_x , σ_y and σ_z are dispersion constants in x, y, z directions respectively.

1. When release is at the ground level;

$$C(x, y, z) = \frac{Q * \exp(\frac{-y^2}{2\sigma_y^2})}{\pi\sigma_y\sigma_z u} \quad (9.13)$$

2. For release at height, H,

$$C(x, y, z) = \frac{Q * \exp(-1/2 * (y^2/\sigma_y^2 + z^2/\sigma_z^2))}{\pi\sigma_y\sigma_z u} \quad (9.14)$$

3. For center-line concentration:

- For release at ground level:

$$C(x, 0, 0) = \frac{Q}{\pi\sigma_y\sigma_z u} \quad (9.15)$$

- For release at height, H:

$$C(x, 0, 0) = \frac{Q * \exp\left(\frac{-H^2}{2\sigma_z^2}\right)}{\pi\sigma_y\sigma_z u} \quad (9.16)$$

4. Maximum ground level concentration above ground level, at H, is given by

$$C_{max} = \frac{2Q}{e\pi u H^2} \frac{\sigma_z}{\sigma_y} \quad (9.17)$$

It occurs at a point $\sigma_z = H/\sqrt{2}$

In the stack height calculation, various wind velocities ranging from 1 to 5 m/s are assumed. The ground level concentration is taken as $80 \mu\text{g}/\text{m}^3$, which is a standard value for SO_2 , which should not be exceeded. Height of stack for various conditions can be easily calculated. Maximum ground level concentration of sulfur oxide allowable = $80 \mu\text{g}/\text{m}^3$.

SO_2 allowable = $80 \mu\text{g}/\text{m}^3$;

C in $\text{mg}/\text{m}^3 = 12.1877 P * M * C_{ppm}/T$

where P = pressure, atm

M = molecular weight

T = temperature, K

From the above equation, C_{SO_2} in ppm = 0.03 ppm

Stack heights are calculated for category 'D' atmospheric stability and is given below [8].

Various steps involved in the stack height are as follows: (1) local wind velocity is assumed, (2) maximum ground level concentration at a particular distance is assumed, and then stack height is calculated. In the present design problem, stack heights are calculated for design A (Chapter 7) assuming wind velocities of 2 and 3 m/s which are the typical values normally encountered, and stability condition 'D'.

Distance from source, 'x' m	Wind velocity, m/s	σ_z	σ_y	Stack height, 'H' m
500	2	15	35	25
500	3	15	35	21
1000	2	27	62	25
1000	3	27	62	21
1500	2	40	100	24
1500	3	40	100	20
2000	2	45	120	23
2000	3	45	120	19

Table 9.2: Stack height calculations

STACK DIAMETER CALCULATION

Exit gas velocity (superficial velocity) is assumed and the stack diameter is calculated based on the volumetric flow rate and temperature at which it is discharged.

Maximum ground level concentration:

$$C_{max} = \frac{2 * Q * \sigma_z}{\pi e u H^2 \sigma_y} \quad (9.17)$$

case (1):

$$x = 500 \text{ m}; u = 3 \text{ m/s}; \sigma_y = 15 \text{ m}; \sigma_z = 35 \text{ m}; C_{max} = 80 * 10^{-6} \text{ g/m}^3$$

$$80 * 10^{-6} = \frac{2 * 1 * 15}{e * \pi * 3 * H^2 * 35}$$

$$H = 21 \text{ m.}$$

CPCB has recommended a minimum stack height of 30 m, for hazardous waste incinerators.

Typical superficial velocity in the stacks ranges from 2 to 2.5 m/s.

$$\text{Volumetric flow rate of air} = \frac{\text{mass of gases leaving}}{\text{density of gaseous mixture}} \quad (9.18)$$

$$\begin{aligned}
 &= \frac{25,360}{\left(\frac{1.29}{0.082 \times 473}\right)} \\
 &= 33,920 \text{ m}^3/\text{hr} \\
 \text{Vol. flow rate} &= (\text{cross sectional area}) * (\text{superficial velocity in the stack}) \\
 33,920 \text{ m}^3/\text{hr} &= \text{C.S.A.} * 2.5 \text{ m/s} \\
 \text{C.S.A.} &= 3.768 \text{ m}^2 \\
 \pi D^2/4 &= 3.768 \text{ m}^2 \\
 \text{Stack diameter, } D &= 2.2 \text{ m}
 \end{aligned}$$

Pressure drop due to friction:

Pressure drop due to friction can be calculated using Fanning's equation assuming that temperature of the gases in the stack is constant [11].

9.3.2 PRESSURE DROP IN THE STACK

Pressure drop in the stack can be calculated as follows:

Diameter of the stack, D	$= 2.2 \text{ m}$
Height of the stack, H	$= 30 \text{ m}$
Velocity of gases in the stack, V_g	$= 2.5 \text{ m/s}$
Temperature of the gaseous stream, T_g	$= 200^\circ\text{C}$
Viscosity of gases @ 200°C , μ	$= 2.4 * 10^{-5} \text{ kg/m-s}$
Density of the gaseous mixture, ρ_g	$= 0.75 \text{ kg/m}^3$
Reynold's number, N_{Re}	$= 171,875$
Equivalent roughness for new concrete pipe, ϵ	$= 0.003 \text{ m}$
ϵ/D	$= 0.0013$
Friction factor	$= 0.0055$

Physical properties of the gaseous mixture is assumed to be that of air and they were taken from Ref [11]. Equivalent roughness parameter for a new concrete pipe and friction factor values were taken from Peters and Timmerhaus (M. S. Peters and K. D. Timmerhaus. *Plant Design and Economics for Chemical Engineers*, Third edition, McGraw-Hill, Inc., Singapore, 1980.)

Fanning equation for pressure drop is

$$\Delta P = 4f \frac{H}{D} \frac{V_g^2}{2g_c} \rho_g \quad (9.19)$$

Pressure drop from the above equation is 1 N/m^2 .

$$\begin{aligned} \text{Pressure drop due to height difference is } \rho_g * g * H &= 0.75 * 10 * 30 \\ &= 225 \text{ N/m}^2 \end{aligned}$$

$$\begin{aligned} \text{Total pressure drop} &= \text{pressure drop due to friction} \\ &\quad + \text{pressure drop due to height difference} \\ &= 226 \text{ N/m}^2 \text{ (1" water column)} \end{aligned}$$

9.4 PICs, PCBs, DIOXINS GENERATION AND THEIR CONTROL

When organic materials are fired, other organic compounds are generated, which were not present in the waste. Apart from these products, incomplete combustion also produce unwanted and polluting products. These are generally termed as PICs, and more notable of these are PCBs, dioxins and dibenzofurans. EPA has identified more than 200 PCBs, amongst them some are potentially toxic and some are not. No specific control technology exists for these organics though it has been found that with good combustion, the generation of PICs is extremely small [5,17].

9.4.1 DIOXIN CONTAINING WASTE

All isomers of chloro dibenzo-p-dioxin (CDDs) are classified as equally toxic and all chlorinated dibenzofurans (CDFs) are also classified equally toxic. Emission of dioxin even in traces is unacceptable. Hence DRE of 99.9999% is suggested for the incineration of CDDs and CDFs. Dioxin and furan generation with temperature is shown in Figure 9.2. This plot was generated by EPA [28] at specific temperatures. It should be interpolated only with caution.

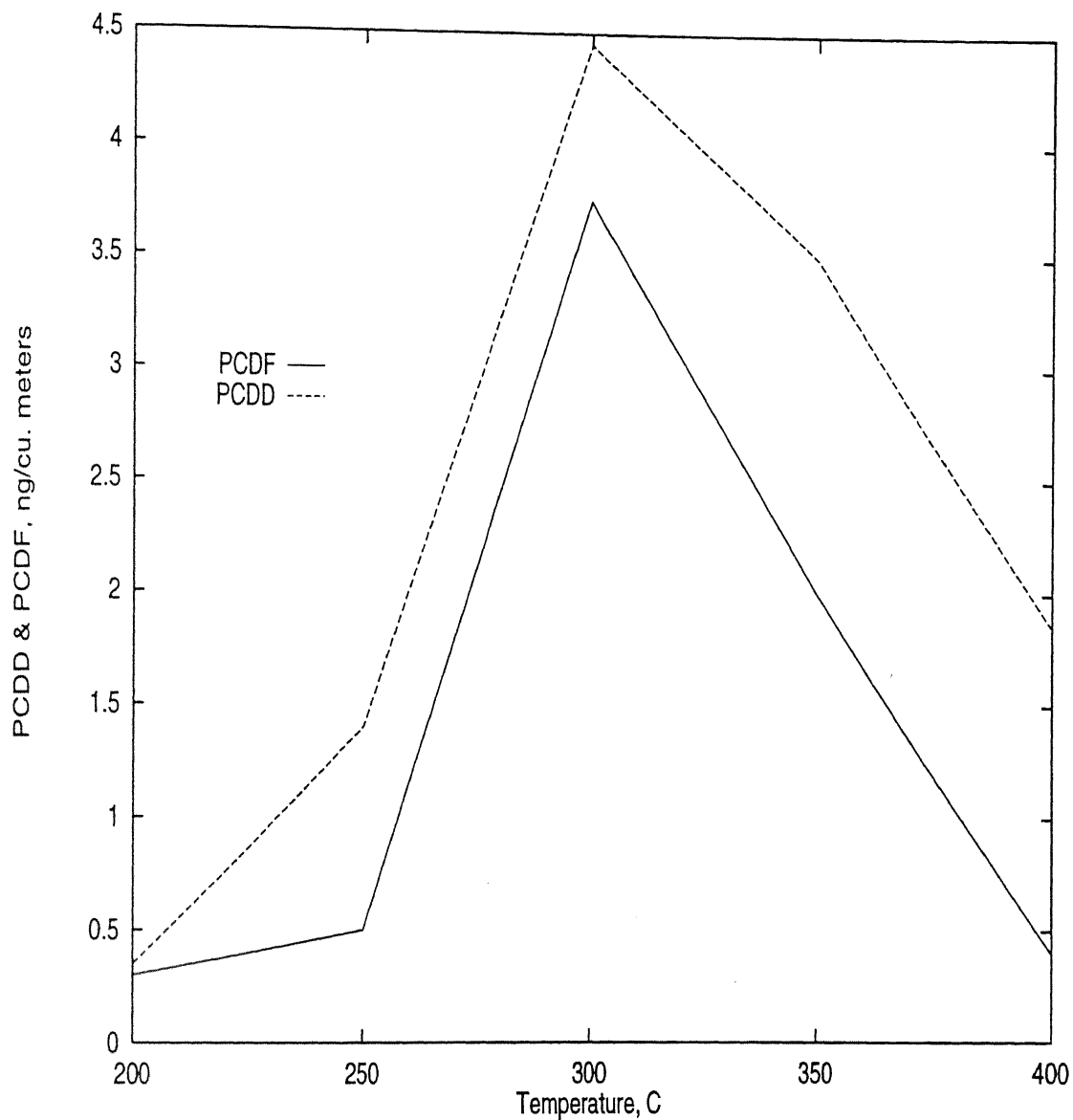


Figure 9.2: Variation of dioxins(PCDD) and furans(PCDF) formed in fly ash in range from 200 to 400 degree Celcius [29].

9.4.2 PCB INCINERATION

The following guidelines are provided by TSCA (Toxic Substances Control Act, USA) for PCB incineration.

1. All PCB containing wastes should be incinerated at or above 1200°C , with a minimum 2 seconds of retention time, and 3 percent of excess oxygen in the exhaust gas [5].
2. Combustion efficiency should always be monitored .
3. PCB charging rate and total feed rate must be monitored at least once every 15 minutes.
4. Temperature should be continuously monitored. when there is a drop in the temperature below 1200°C or oxygen percent in the exhaust gas below 2 percent, PCB feed rate should automatically cease.
5. The following stack emissions should be monitored: (1) oxygen; (2) CO & CO_2 ; (3) oxides of nitrogen; (4) HCl ; (5) total chlorinated organic constituents; (6) PCBs and (7) particulate matter.

Water scrubbers or equivalent gas cleaning equipment should be used to control HCl emissions. Spent scrubber water should be monitored to comply with effluent standards. If the PCBs to be monitored are non-liquid, in addition to the above requirements, the emission discharge should not be greater than one kg of PCB per million kg of PCBs charged into the furnace. Continuous Emission monitoring techniques are very well discussed by Jhanke [29].

9.4.3 DIOXIN AND FURAN EMISSIONS

Apart from dioxin present in the waste, it may be generated during the combustion process. Many explanations for the formation have been put forth [28].

Formation of PCDD and PCDF takes place at temperatures ranging from 200 to 400°C. Figure 9.2 shows no effects on dioxins and furans below 200°C, a sharp peak in both dioxins and furans which occurs at 300°C and their destruction at 400°C. Oxygen concentration influences formation of dioxins. Zero oxygen results in no formation, increasing oxygen levels results in a reduction in the fraction of dioxins and furans having more toxic four-chlorine forms and an increase in fraction of less toxic forms having 6 to 8 chlorine molecules attached.

Chapter 10

INCINERATOR RESIDUE/ASH MANAGEMENT

Some people see things as they are and ask why.

I see things that never were and ask why not.

J. F. Kennedy, in his inaugural speech, 1961.

Incinerator ash may be hazardous. Incinerator ash may contain high levels of several highly toxic metals, dangerous levels of dioxins, etc. Some metals -lead and cadmium, in particular- are readily leachable from ash at levels that frequently exceed the limits defining a hazardous waste. Incineration increases metal concentration in the ash and can create dioxins, opening up several pathways of exposure to these toxins. So, it is very important to understand the ash management techniques and disposing it off safely. The most fundamental and important measure of ash toxicity is its total toxic metals and dioxin content, given the potential for direct exposure (e.g.: inhalation and adsorption into the direct ingestion of toxin laden ash particles). Indeed, a full accounting of the hazards of ash posed during all phases of its management requires the knowledge of its total chemical composition.

The amount of metals in the waste stream before incineration must be equal to the sum of their amounts in the air emissions and ash left after incineration. The process of incineration destroys essentially the bulky matrix - paper, plastics, organic constituents

and other materials. Incineration is however is uniquely unsuitable for managing metals. In addition to metals, highly toxic dioxins may come with incineration fly ash [30].

While dioxins appear to be lower in fly ash from newer facilities, the ability of such facilities to consistently achieve acceptable low levels remains to be demonstrated [28]. As is the case for metals, more efficient air pollution control devices will act to increase the concentration of dioxins detected in ash residues. In addition combustion controls designed to increase burnout and reduce dioxin formation may also increase ash toxicity. Hence, we have to minimize the the fly ash dioxin content to allowable limits and toxic ash can be safely disposed off.

10.1 LEACHABILITY OF METALS PRESENT IN INCINERATION ASH

The leachability of metals present in incineration ash is a measure of its hazard. EPA [28] has tested more than 30 incinerators ash samples and these data demonstrate the following:

- Almost every sample of fly ash tested exceeds federal standards defining a hazardous waste, usually for both lead and cadmium.
- Half of the combined fly and bottom ash samples tested also exceed the standards, typically for lead.

The increased leachability of metals in incineration ash arises from several phenomena associated with combustion. First several toxic metals are volatilized and condensed onto the surface of fly ash particles and their concentration increases with decreasing particle size.

Certain toxic metals -most notably lead- are readily soluble in water under highly alkaline conditions: significant solubility at low pH values (for example, gas scrubbing section sludge with trapped fly ash particles). Because of the solubility of the toxic constituents

present in the waste is high, proper care should be taken, before disposing it off. Complete composition analysis of the ash should be done. Depending on the hazardous constituents, their composition, etc., suitable landfilling method, landfill covering layer thickness, safety precautions to be considered, etc., could be enlisted prior to landfilling [28].

10.2 ROUTES OF EXPOSURE TO INCINERATION ASH

Here some of the possible and highly relevant exposure pathways are given. Ash exposure to the atmosphere, ground water, etc., can be enumerated as follows.

Ash discharge and spillage occur during the following stages.

1. On site handling from the time of generation (e.g.: (1) ash collection from incineration, (2)cyclone separators, gas scrubbers, ESPs, stacks, etc.).
2. Ash storage
3. Transportation, loading, unloading, etc.
4. Handling and depositing at the landfill until the time of final cover.

Numerous studies on other waste similar to ash such as metal smelter dusts demonstrate that improper management- even long after initial disposal- can result in actual human exposure to toxic metals through such pathways [30].

10.3 ASH MANAGEMENT

Incineration reduces the volume and weight of the hazardous constituents. In most of the cases, the ash is also a highly hazardous one. For effective management and disposal of ash the following techniques are suggested.

10.3.1 ASH CHARACTERIZATION

Like waste characterization incineration residue can also be characterised. The composition of ash, elemental constituents, toxicity, etc., can be tabulated and appropriate actions can be taken. This will be helpful in transportation of ash to landfill site, in the design of landfill layer thickness, etc.

10.3.2 METALS ISOLATION

Metals isolation can be done prior to incineration. As far as possible, metallic constituents from hazardous wastes should be removed in the pretreatment processes. If it is not possible, an attempt should be made to remove from the incineration residue. This will reduce the volume of ash to be safely landfilled, and the metal may be recycled.

10.3.3 REGULATIONS FOR ASH DISPOSAL

Local regulations should be laid down for ash handling and disposal. Before giving permit to the incineration plants, proper ash disposal facilities available nearby should be assessed. Allowable amount of toxic metals, dioxins, etc., in the residue should be clearly specified.

Chapter 11

STARTUP, SHUTDOWN, OPERATION AND SAFETY

What you don't have can't leak.

Trevor Kletz

All the necessary prerequisites for efficient combustion and minimization of contaminant discharge are provided in a properly designed and maintained incinerator. For all practical purposes the discharge of smoke, pollutant gases, solid contaminants, etc., is almost entirely dependent on the actions of the operator.

11.1 STARTUP

The most important single aspect of the operation of incinerators is charging refuse into the incineration chamber. If refuse is charged and then ignited, it will take some time to catch fire and reach steady state. During this time large amount PICs are generated. Fly ash carryover is also very high. To avoid this, the following simple procedure is suggested for startup of the plant.

1. Ensure that grate(s) and ash pit are cleaned.
2. Manhole, access door, etc., are closed.

3. Start the blower and send sufficient amount of air into the furnace.
4. Pump in the fuel and ignite the air-fuel mixture, wait for sometime for the temperature to be at least 500°C
5. Now start the absorption recycling solution at the scrubbing section.
6. Ensure that nowhere leakage occurs.
7. Send the waste in slowly. See whether the combustion occurs properly through the glass door.
8. Analyse the gas emission immediately and find whether they are within the acceptable limits.
9. If not, adjust operating parameters like blower speed, residence time, fuel rate into the furnace, etc., to ensure that complete combustion takes place.
10. Before starting up a plant ensure fire fighting equipment availability and their condition.
11. Ensure waste is spread on the entire grate(s), not piled on a particular area.

11.2 SHUTDOWN

Normally five days a week, two shifts a day plants require frequent startup and shutdown (one each for startup and shutdown per day). Hence shutdown procedures should also be clearly specified. The following simple procedure is suggested for shutdown of an incinerator plant.

1. Stop waste feeding slowly.

2. After stopping waste feeding completely, ensure that the solids are completely combusted in the furnace by seeing through the glass door.
3. Now stop the fuel flow into the primary furnace and after sometime stop fuel flow for secondary chamber also.
4. Then stop the liquid circulation in the scrubbing section.
5. All along, emissions through stack should be carefully monitored.
6. Then stop air circulation through the system.
7. Clean the grates and collect ash from ash pit.
8. Seal the collected ash in containers, label them, and send them for safe disposal.

11.3 OPERATION

The following guidelines should be followed during operation.

1. Continuously monitor the stack emissions through CEMs (Continuous Emission Monitoring equipment/systems).
2. Maintain negative draft in the primary and secondary chambers to ensure that if at all any leak occurs, it is air into the system, not the other way (i.e., hot fumes and gases do not go out of the system to the atmosphere).
3. Seal the ash collection section.
4. Ensure that the ash collection pit is not over-filled with ash. If this occurs, solid waste movement in the grates get severely affected, resulting in PICs generation and improper combustion.
5. Ensure that the toxic gases removal efficiency is maintained.

6. Ensure that the fuel is supplied continuously.

11.4 CLEANING OF THE INCINERATOR

Cleaning of the incinerator plays an important role in its efficient operation.

1. Before entering into the vessel ensure that no waste or ash is present in the grates by seeing through the glass door.
2. Close all fuel and feeding sections inlets.
3. Pass air through the system and test for the presence of ignitable vapours.
4. Purge the system with pure nitrogen.
5. Assured the above that no combustible and toxic gases are present, enter into the vessel
6. When a person is inside the vessel, he should wear safety clothings, breathing apparatus, safety glasses, shoes, etc.

The following are to be checked during maintenance operations.

1. Metallic sections present apart from the refractories, and their stability, corrosion if any, etc.
2. Condition of the refractories.
3. Burner plugging and burner conditions.
4. Temperature measuring sensors.
5. Pipelines, bends, potential leakage occurring points, etc.
6. Solid slag sticking to grates, or side walls, drop holes, pipelines, feed chute walls, etc.

If fire occurs, air blowers should be stopped immediately. Then fuel and waste are fed to the incinerator. Adequate fire fighting equipment, trained personnel and their availability are very important. All personnel involved in the plant operation should follow well laid down safety rules very strictly, neglecting whatever difficulties they face during wearing the safety equipment.

Atmospheric air in the plant area should also be periodically checked to ensure that no leakage of combustibles and/or toxic gases occurs. The following equipment should be kept in well maintained condition always.

1. Fire fighting equipment
2. Breathing apparatus
3. Safety clothings, safety shoes & glasses.
4. Emergency alarms

11.5 TRANSPORTATION OF HAZARDOUS WASTES

As far as possible, incineration plants should be located far away from the residential area. Be it common treatment plant, landfill area, etc., hazardous materials transported from various sources to these plants and ash generated should also be sent for safe landfilling. Hence proper care should be taken in transporting hazardous wastes. Some important factors to be considered are suggested for safer transportation of hazardous wastes.

1. Existing hazardous material procedures can be modified as necessary and adopted for transportation of hazardous wastes/ash residue.
2. Different colors for different type of wastes to indicate their toxic/explosive potential.

3. Like MSDS (Material Safety Data Sheet), waste data sheet should be prepared and should be carried along with vehicles which can be made mandatory for hazardous waste (these are used abroad).
4. Vehicles should carry enough fire fighting equipment, breathing apparatus, leakage prevention apparatus, etc.
5. Special permit system for hazardous waste container vehicles, special license for drivers, etc., may minimize the risks involved
6. Periodic maintenance of valves and leakage checking regularly during transportation to ensure no material leaks out because of some unknown reasons.
7. Spillage prevention during loding and unloading of waste and ash.
8. Training the personnel involved in these oprertions for the worst possible cases.
9. Analysing various worst possible cases, we could develop a chart what to do if a particular type of accident occurs, and whom to contact, etc. Risks involved and potential damages can thus be minimized.

Apart from developing good procedures for startup, shutdown, cleaning, and transportation, they should be reviewed on a continuous basis, for example, once in six months or so. Unit to unit, section to section basis HAZOP (HAZard and OPerability studies), FTA (Fault Tree Analysis) and ETA(Event Tree Analysis), WHAT-IF analysis, etc., can be done and existing safety setups/systems can be modified to improve system reliability and safety [31, 32]. Some of following important factors should be considered.

1. Good training for operating personnel.

2. Instructing the people living nearby about facts, chemicals and their effects, precautions to be taken in case of emergency, instead of trying to conceal the potential hazards involved (Government should enforce this as a mandatory requirement).
3. Mock drills for the people inside the plant and also for those living nearby.

Incineration plants should be operated with best possible technology, equipment and personnel, and well laid down operating procedures. It is very important because the hazards involved in these plants are high in terms of possibility, probability and quantity. All along, during startup, shutdown, operation, transportation, ash handling, gas treatment, etc., well trained operating personnel should be employed and they should be well prepared to manage the worst possible accidents.

Chapter 12

CONCLUSIONS

The woods are lovely, dark and deep;
but I have promises to keep;
and miles to go before I sleep;
miles to go before I sleep.

Robert Frost

The very first step in hazardous waste management is to know the characteristics of the waste. A new coding mechanism for different wastes and waste index to identify the characteristics/potential hazards of the wastes are suggested. This waste index would be of great help in understanding the nature of the waste and also in the design of any waste disposal system, waste/ash transportation, handling, etc.

Two types of incinerators are designed. They are: (1) grate furnace incinerator for toxic organics (CPCB Waste Category 12) and (2) multiple hearth furnace incinerator for pesticide industry waste (CPCB Waste Category 15). Design of both incinerators show that fuel requirement for complete combustion are very high, even though the heating values of the wastes are high. When the calorific value of the waste is low, fuel requirements for complete burning shoots up.

Apart from the design of incinerators, operating parameter evaluation is very important. Capital investment cost for an incinerator plants is higher than any other hazardous waste disposal method. Hence it should be used only when its cost can be justified, or subsidies provided by the Government. There may be an incinerator serving a whole industrial area. CO_2 is the least harmful of the combustion products. However there is a school of thought that it causes global warming. Hence, a green cover of lots of trees around the incinerator will help in absorbing CO_2 and minimizing its effect on global warming.

12.1 SCOPE FOR FUTURE WORK

Some of the promising areas of research are given below.

12.1.1 WASTE CHARACTERIZATION

Some important aspects of waste characterization are discussed in detail in the third chapter. More precise characterization methods are necessary to properly understand the characteristics of the waste.

12.1.2 DESIGN OF INCINERATORS

Almost all the existing designs in the field of incineration are done on the basis of complete combustion, high temperature and sufficient residence time for solids, gases, etc. Combustion modeling is very difficult because of the number of constituents present in the waste and their interactions with other constituents in the waste during combustion, etc. Very few correlations are available for excess air, residence time calculations, and desired temperature. If some empirical correlations or models predict as to why the temperature should be $1,000^\circ C$ or so, and why not less temperatures, then enormous amount of energy savings could be made.

If heavy metals are present in the waste they strongly catalyse the reactions resulting

in considerable gaseous pollutants. Their separation from the waste before combustion may eliminate this hazard. Environmental impact assessment of any proposed incinerator should be done to see its possible impact on the environment and steps taken to minimize those and keep within the permissible limits.

12.1.3 ASH CHARACTERIZATION

Characterization of potentially toxic and highly concentrated ash, fly ash & sludge generated in the gas treatment section should be done for various wastes.

12.1.4 WASTE MINIMIZATION

Case to case basis hazardous waste analysis to know: (1) how the waste is generated; (2) is there any way to prevent their generation?; (3) is there any way to minimize their generation?; (4) recycling and reusing options, etc., may throw some light into the field of waste minimization, because most of the wastes are generated because of mal operations, false procedures unawareness among the personnel involved, etc.

12.1.5 HAZARDOUS WASTE/ASH RESIDUE TRANSPORTATION

Present hazardous material transportation procedures may be slightly modified and applied for transportation of hazardous wastes and ash residue.

12.1.6 SOFTWARE DEVELOPMENT FOR DESIGN

The major problems involved in the design of incinerators are that the rate expressions for various wastes burning are not available. If we have rate expressions for various wastes' combustion and their possible effects on other constituents at the burning conditions, a good design of incinerators could be obtained. Software can then be developed to help in the design.

APPENDIX-A

GLOSSARY

Acute toxicity Any poisonous effect produced within a short period of time, usually 24 to 48 hours, resulting in severe biological harm and often death.

Bottom ash The residual material that is left on the hearth, or falls off the grate of an incinerator after burning is complete.

CEM Continuous Emission Monitoring.

CPCB Central Pollution Control Board

DE Destruction Efficiency.

DRE Destruction and Removal Efficiency.

Draft The difference between the pressures within an incinerator and that in the atmosphere.

ESP Electrostatic Precipitator.

Grate A part of an incinerator used to support solid waste, or solid fuel drying, igniting, or burning.

Hearth The bottom of the furnace, upon which the waste material is exposed to the flame.

Heavy metals Metallic elements, with high atomic weight, such as lead, cadmium, etc., which tend to accumulate in the food chain.

Incineration Controlled combustion process to thermally destruct waste materials.

Incinerator stoker A mechanically operated moving grate for supporting, burning, or transporting solid waste in a furnace and discharging the residue.

Landfill A land disposal site.

MBH Million Btu per Hour.

PCB Poly Chlorinated Biphenyls.

PICs Products of Incomplete Combustion.

Proximate analysis One of the waste analysis methods used to find moisture, volatile matter, fixed carbon and ash content on weight percent basis.

Pyrolysis The chemical decomposition of organic matter through application of heat in an oxygen deficient atmosphere.

Over-fire nozzles Nozzles located few centimeters above the grates.

Reactivity The tendency to create vigorous reactions with air, or water, or tendency to explode.

Refractory Non-metallic materials used in the lining of furnaces to withstand very high temperatures.

Scrubber Equipment used to remove impurities from a gaseous stream.

Secondary combustion chamber A furnace which receives effluent gases from a primary furnace, used to minimize PICs generation and to improve combustion efficiency.

Turn down The ratio of waste combusted to gases to the waste charged.

Ultimate analysis One of the waste analysis methods used to find out the elemental composition of the waste (e.g.: carbon, oxygen, nitrogen, etc.).

Waste index A newly proposed mechanism to identify waste properties on the basis of an index.

APPENDIX-B

Table A.1: CPCB waste categories

Waste categories	Type of wastes	Regulatory Quantities
Waste Category No. 1	Cyanide wastes	1 Kilogram per year calculated as cyanide
Waste Category No. 2	Metal finishing wastes	10 Kilograms per year the sum of the specified substance calculated as pure metal
Waste Category No. 3	Waste containing water Soluble chemical compounds of lead, copper, zinc, chromium, nickel, selenium, barium and antimony	10 Kilograms per year the sum of the specified substance calculated as pure metal
Waste Category No. 4	Mercury, arsenic, thallium and Cadmium bearing wastes	5 Kilograms per year the sum of the specified substance calculated as pure metal
Waste Category No. 5	Non-halogenated hydrocarbons including solvents	200 Kilograms per year calculated as non-halogenated hydrocarbons
Waste Category No. 6	Halogenated hydrocarbon including solvents	50 Kilograms per year calculated as halogenated hydrocarbons
Waste Category No. 7	Wastes from paints, pigments, glue, varnish and printing inks	250 Kilograms per year calculated as oil emulsions
Waste Category No. 8	Wastes from dyes and dye intermediates containing Inorganic chemical compounds	200 Kilograms per year calculated as Inorganic chemicals
Waste Category No. 9	Wastes from dyes and dye intermediates containing Inorganic chemical compounds	50 Kilograms per year calculated as Inorganic chemicals
Waste Category No. 10	Waste oil and oil emulsions	1000 Kilograms per year calculated as oil and oil emulsions
Waste Category No. 11	Tarry wastes from refining and tar residues from distillation or pyrolytic treatment	200 Kilograms per year calculated as tar
Waste Category No. 12.	Sludges arising from treatment of wastewaters containing heavy metals, toxic organics, oils, emulsions and spent chemicals and Incineration ash	Irrespective of any quantity

Waste Category No. 13	Phenols	5 Kilograms per year calculated as phenols
Waste Category No. 13	Phenols	5 Kilograms per year calculated as phenols
Waste Category No. 14	Asbestos	200 Kilograms per year calculated as asbestos
Waste Category No. 15	Wastes from manufacturing of pesticides and residues from pesticides and herbicides formulation units.	5 Kilograms per year calculated as pesticides and herbicides and pesticides and their intermediate residues from pesticides and products herbicides formulation units
Waste Category No. 16	Acidic/alkaline/slurry	Wastes 200 Kilograms per year calculated as acids/alkalies
Waste Category No. 17	Off-specification and discarded products	Irrespective of any quantity
Waste Category No. 18	Discarded containers and container liners of hazardous and toxic wastes	Irrespective of any quantity

APPENDIX-C

Some of the very interesting web sites of incineration and incinerators, incinerator manufacturing companies, etc., are given in this appendix.

- EPA's Proposed Medical Waste Incinerator Rule. The Environmental Protection Agency (EPA) has extended to the Summer of 1997 the estimated completion date..
[http : //www.afcee.brooks.af.mil/proact/main/cross/ed28/ED283.HTM](http://www.afcee.brooks.af.mil/proact/main/cross/ed28/ED283.HTM)
- An alternative to northwest incinerator: Reducing Waste, Stimulating Economic Development and Creating Jobs Instead of Pollution. By. Bill Eyring,...
[http : //www.cnt.org/susman/incinerator.html](http://www.cnt.org/susman/incinerator.html)
- Lab-Scale CELSS Incinerator Lab-Scale CELSS Microwave Incinerator. The Technology. The microwave incinerator consists of two combustion chambers and a catalytic oxidizer. Waste... *[http : //brad.arc.nasa.gov/Hardware/Incinerator.html](http://brad.arc.nasa.gov/Hardware/Incinerator.html)*

Some of the interesting world wide web addresses are given below.

- *[http : //brad.arc.nasa.gov/Hardware/IncinInterior.html](http://brad.arc.nasa.gov/Hardware/IncinInterior.html)*
- *[http : //brad.arc.nasa.gov/Hardware/Incinvenky.html](http://brad.arc.nasa.gov/Hardware/Incinvenky.html)*
- *[http : //brad.arc.nasa.gov/Hardware/IncinExhaust.html](http://brad.arc.nasa.gov/Hardware/IncinExhaust.html)*
- *[http : //brad.arc.nasa.gov/Hardware/Schematics/Incin.html](http://brad.arc.nasa.gov/Hardware/Schematics/Incin.html)*
- *[http : //brad.arc.nasa.gov/Hardware/Schematics/LPBupIncin.html](http://brad.arc.nasa.gov/Hardware/Schematics/LPBupIncin.html)*
- *[http : //brad.arc.nasa.gov/Hardware/IncinCart.html](http://brad.arc.nasa.gov/Hardware/IncinCart.html)*
- *[http : //www.edf.org/pubs/EDF-Letter/1993/May/alyield.html](http://www.edf.org/pubs/EDF-Letter/1993/May/alyield.html)*
- *[http : //rhic2.physics.wayne.edu/stuntz/home.html](http://rhic2.physics.wayne.edu/stuntz/home.html)*

- <http://www.envirobiz.com/newsdaily/960509a2.htm>
- <http://www.pmrma - www.army.mil/htdocs/cleanup>
- <http://www.fluent.com/Newsletters/NewsWinter96/ABB.html>
- <http://net.unl.edu/swi/pers/kimball.html>
- <http://net.unl.edu/swi/pers/louisville.html>
- <http://www.dep.state.pa.us/dep/deputate/pollprev/franklin/bfpage56.htm>
- <http://www.lcv.org/greenbook/sq.recyc.html>
- <http://www.pmrma - www.army.mil/htdocs/cleanup/>
- http://www.edf.org/pubs/EDF - Letter/1993/Sep/e_closeinc.html
- <http://www.doubleclickd.com/Articles/incinerator.html>
- <http://rtk.net/E9724T660>
- <http://www - personal.umich.edu/babyfish/>
- <http://www.eq.state.ut.us/eqshw/incin1.htm>
- http://ce.ecn.purdue.edu/TAP/Programservices/Projects/floyd_hospital.html
- <http://www - emtd.lanl.gov/td/userfac/ContolledAirIncinerator.html>
- http://www.edf.org/pubs/EDF - Letter/1992/Jan/g_a sh.html
- http://www.edf.org/pubs/EDF - Letter/1989/Aug/l_detroit.html
- <http://www.env.gov.bc.ca/epd/cpr/regs/wrbreg.html>

Bibliography

- [1] E. D. Martin and J. H. Johnson. *Hazardous Waste Management Engineering*. Van Nostrand Reinhold company, New York, 1987.
- [2] N. C. Hass and R. J. Vamos. *Hazardous and Industrial Waste Treatment*. Prentice-Hall, Englewood Cliffs, New Jersey, 1995.
- [3] Metcalf and Eddy. *Waste Water Engineering: Treatment, Disposal, Reuse*. Tata-McGraw Hill, New Delhi, 1979.
- [4] G. Tchobonoglous, H. Thiesen, and R. Eliassen. *Solid Wastes: Engineering Practices and Management Issues*. McGraw Hill, Inc, New York, 1977.
- [5] C. R. Brunner. *Hazardous Waste Incineration*. McGraw Hill, Inc, New York, 1993.
- [6] Executive Summary. *Inventorization of Hazardous Waste Generation in Five Districts of Gujarat*. National Productivity Council, New Delhi, 1994.
- [7] Anonymous. *Dow's Fire and Explosion Hazard Classification Guide*. AICHE Technical Manual, New York, 1994.
- [8] J. P. Gupta. *A Short Course on Quantitative Risk Assessment and Hazard Analysis*. IIT Kanpur, Kanpur, 1993.
- [9] Anonymous. *Handbook of Chemical Hazard Analysis*. U. S. Government Printing Office, Washington, D.C., 1990.

- [10] R. C. Corey. *Principles and Practices of Incineration*. John Wiley & Sons, Inc, New York, 1969.
- [11] R. H. Perry and D. Green. *Chemical Engineers' Handbook*. McGraw Hill, Inc, New York, 1984.
- [12] W. R. Nissien. *Combustion and Incineration Processes*. Marcel Dekker, Inc, New York, 1978.
- [13] Anonymous. *Proceedings of 1968 National Incinerator Conference*. ASME, New York, 1968.
- [14] J. H. Bayer. New routes for hazardous waste management. *Pollution Engineering*, 16(4):25-27, 1984.
- [15] C. A. Wentz. *Hazardous Waste Management*. McGraw Hill, Inc, New York, 1989.
- [16] T. J. Sorg and H. L. Hicknman. *Sanitary Landfill Facts*. U.S. Public Health Service, Washington, D.C., 1970.
- [17] E. T. Oppelt and C. R. Dempsey. Incineration of hazardous wastes: A critical review update. *Air & Waste*, 43:27-71, 1993.
- [18] F. M. Holloway. On-site vs off-site waste disposal. *Pollution Engineering*, 16(9):28-32, 1984.
- [19] J. H. Munoz, J. L. Tessitore, and F. Cross. Polychlorinated biphenyls destruction by incineration. *Pollution Engineering*, 19(8):70-75, 1987.
- [20] R. E. Kenson. Rotary kiln incinerator for sludge disposal. *Pollution Engineering*, 13(12):44-45, 1981.

- [21] J. P. Reynold, R. R. DuPont, and L. Theodore. *Hazardous Waste Incineration Calculations: Problems and Software*. John Wiley & sons, Inc, New York, 1991.
- [22] C. R. Brunner. Find heating value using chemical oxygen demand. *Pollution Engineering*, 18(3):34–36, 1986.
- [23] D. M. Himmelbleau. *Basic Principles and Calculations in Chemical Engineering*. Prentice-Hall, Inc, Englewood Cliffs, New Jersey, 1979.
- [24] R. H. Barnes, R. E. Barrel, A. Levy, and M. J. Saxton. *Chemical Aspects of Afterburner Systems*. US EPA, Durham, N.C., 1979.
- [25] General Electric Company. *Solid waste disposal technology assessment*. General Electric Company, 1979.
- [26] A. K. Khol and F. Riesenfeld. *Gas Purification*. Gulf Publishing Company, Houston, 1985.
- [27] A. Stern. *Air Pollution*. Academic press, Inc, New York, 1986.
- [28] F. Hasselriis. How control of combustion emissions and ash residues from municipal solid waste can minimize environmental risk. *AIChE Symposium series*, 265(18):154–167, 1988.
- [29] J. H. Jhanke. *Continuous Emission Monitoring*. Van Nostrand Reinhold Company, New York, 1993.
- [30] R. A. Denison. The hazards of municipal incinerator ash and fundamental objectives of ash management. *AIChE Symposium series*, 18:148–153, 1988.
- [31] D. Crowl and J. F. Louvar. *Chemical Process Safety: Fundamentals with Applications*. Prentice-Hall, New Jersey, 1990.

- [32] F. P. Lees. *Loss Prevention in Process Industries*. Butterworths, London, 1980.